



## Danish seine – Ecosystem effects of fishing

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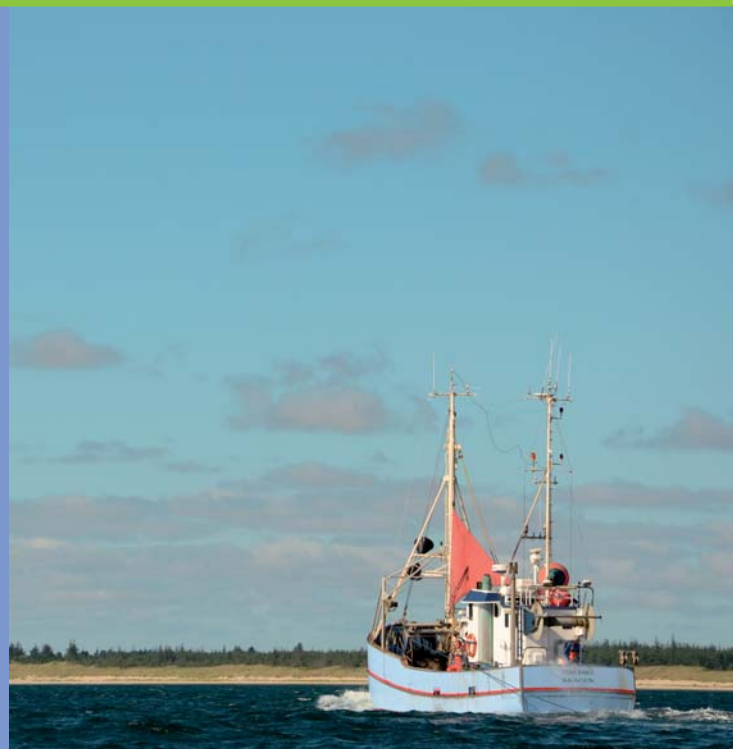
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# Danish seine - Ecosystem effects of fishing

PhD Thesis



Written by Thomas Noack  
Defended 7 March 2017

# **Danish seine – Ecosystem effects of fishing**

Ph.D. Thesis by

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Hirtshals, Denmark

December 2013 – December 2016



## Preface

The present thesis is submitted in partial fulfillment of the requirements for obtaining the Doctor of Philosophy (Ph.D.) degree. The thesis consists of a synopsis and four supporting papers. One paper is published and three are submitted for publication.

I wish to express my sincere thanks to my supervisors Ludvig Krag and Kai Wieland from DTU Aqua – Ludvig especially for his excellent way of guiding me through the last three years of my career, and Kai for his willingness to help by taking over the job of co-supervising me.

Moreover, I wish to thank:

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- ✍️ Rikke Frandsen for her great job in co-supervising me for more than 1.5 years
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- ✍️ Bent Herrmann, the man to ask any statistics-related question and
- ✍️ Bernd Mieske, Daniel Stepputtis and Juan Santos, my colleagues and friends from Germany, who also supported me before, during and after my sea trials

Furthermore, I’d like to say “Thank You” to my girlfriend Franzl, whose tasks ranged from general motivating jobs over testing trial setups in the kitchen up to reviewing manuscripts...amazing job, amazing woman! Last but not least, I’d like to thank my family, always being there for me, and to my brother in specific for being so helpful in conducting preliminary tests of exciting trial setups.

The financial support granted by DTU Aqua and the Ministry of Environment and Food of Denmark to conduct the research described in the supporting papers is greatly acknowledged.

Hirtshals, December 2016



Thomas Noack



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## List of papers

- Paper I:** Noack, T., Stepputtis, D., Madsen, N., Wieland, K., Haase, S., Krag, L.A., In review. Describing the gear performance of a commercial Danish anchor seine. (submitted to ICES Journal of Marine Science)
- Paper II:** Noack, T., Frandsen, R.P., Krag, L.A., Mieske, B., Madsen, N., 2017. Codend selectivity in a commercial Danish anchor seine. Fisheries Research 186, Part 1: 283-291.
- Paper III:** Noack, T., Madsen, N., Mieske, B., Frandsen, R.P., Wieland, K., Krag, L.A., In review. Estimating unaccounted selectivity for fish and invertebrates in a Danish anchor seine. (submitted to ICES Journal of Marine Science)
- Paper IV:** Noack, T., Eggers, F., Madsen, N., Frandsen, R.P., Wieland, K., Krag, L.A., In review. Fishing profiles of Danish seiners and bottom trawlers in relation to current EU management regulations. (submitted to Fisheries Management and Ecology Journal)



## Dansk resumé

Snurrevodsfiskeri er en fiskemetode, som blev opfundet i Danmark for mere end 150 år siden, og som stadig anvendes i vid udstrækning både i Danmark og i andre lande over hele verden. På grund af rapporterede positive egenskaber som høj brændstoeffektivitet, høj fangstkvalitet og lav miljøpåvirkning har snurrevodsfiskeriet opnået stigende opmærksomhed i de senere år. Alligevel findes der kun få videnskabelige undersøgelser om snurrevodsfiskeriet og mange konklusioner baserer sig på antagelser og formodninger. Snurrevoddet er anderledes end et bundtrawl, fordi det ikke benytter trawlskovle, men to lange vodtove til at drive fisk sammen i fiskeriområdet. Det udfordrer eksisterende redskabsovervågningssensorer, som anvendes i bundtrawlfiskeriet. For at opnå viden om snurrevodsfiskeriet og snurrevoddets virkninger på havmiljøet er der blevet udført forskellige eksperimenter under kommercielle forhold, samt omfattede metodeudviklinger til detaljerede dataindsamlinger. Dette muliggjorde studier af fiskeriprocessen med et snurrevod, som viste, at fisk svømmer ind i snurrevoddet meget sent, og at observerede virkninger på havbunden eksperimentelt syntes at være lave, og at kvantificere selektiviteten i voddet, hvilket der ikke tidligere er redegjort for, samt endelig en sammenligning af selektive karakteristika og fiskeri profiler mellem snurrevod og bundtrawl, som er det vigtigste demersal fiskeredskab i verden i dag. Nærværende Ph.D. afhandling med titlen ”Snurrevod - Økosystem effekter af fiskeri” består af en sammenfattende synopsis og fire artikler.

Artikel 1 sammenfatter resultaterne af et sæt testsejladser, hvor forskellige sensorer og kameraer blev brugt til at beskrive fiskeriproceduren med snurrevoddet, når fiskene svømmer ind i voddet og om fiskere kan gennemføre et effektivt fiskeri, selvom de ikke bruger overvågningsudstyr. Resultaterne indikerede, at fiskere kan gennemføre deres mere eller mindre blinde drift af vodtove og vod godt med det formål at maksimere effektiviteten. Endvidere viste resultaterne, at virkningerne på havbunden ved snurrevodsfiskeri er mindre end ved bundtrawlfiskeri.

Et andet sæt testsejladser blev udført for at undersøge selektivitetskarakteristika med en kommerciel snurrevodsfangstpose (Artikel 2). Vurderingen af selektivitetsparametre og selektivitets kurver viste, at selektiviteten ofte blev bedst beskrevet ved

brug af mere komplicerede selektivitetsmodeller, der kombinerer to eller tre logistiske modeller hvilket indikerer en multipel selektivitetsproces. Selvom dette er anderledes i forhold til bundtrawlstudier, hvor simple logistiske modeller normalt bruges til at beskrive selektivitet, var estimer af selektivitetsparametrene lignende for begge fiskeredskaber.

Artikel 3 undersøgte effekter af snurrevoddet på individer, der undslipper fra nettet, før de når fangstposen ved at montere småmaskede opsamlingsposer på forskellige dele af voddet. Resultaterne viste, at når man kun betragter fangsten i fangstposen, vil denne fangst ikke kunne redegøre for betydelige interaktioner med individer af flere forskellige arter fisk og især bunddyr. De fleste fisk undslap gennem det nedre panel i den bageste del af nettet, men mange bunddyr undslap fra de nedre paneler i den forreste del af redskabet. Synlige skader blev registreret på bunddyr for at angive karakteren af påvirkningen og for at angive potentiel dødelighed efter kontakt med redskabet, hvilket i dag er en ubeskreven dødelighed. De observerede skader på fangede organismer var generelt lave.

Artikel 4 anvendte data fra observatørture til sammenligning mellem snurrevodsfartøjer og bundtrawlere i form af fiskeri karakteristika og fangst af konsum arter. Det vigtigste resultat af denne fremgangsmåde var, at snurrevodsfiskeri er en effektiv metode til at fange rødspætter (*Pleuronectes platessa*) og andre fladfisk, men er begrænset i forhold til fiskeriområder. Derimod fiskede trawlerne i flere forskellige områder og var målrettet flere arter. Forskellen i mængden af fisk under mindstemålet var små mellem begge redskabstyper og mellem forskellige maskestørrelser, men yderligere faktorer og en høj random effekt spillede en vigtig rolle i fastlæggelsen af disse.

## **English summary**

The Danish anchor seine is a traditional fishing method that was invented in Denmark more than 150 years ago, and is still extensively used in Denmark and other countries worldwide. Due to reported positive characteristics, like high fuel efficiency, high catch quality and low environmental impacts, Danish anchor seining has gained increasing attention in recent years. However, only few scientific studies have considered Danish anchor seining and several aspects about its operation and interaction with the ecosystem are based on assumptions. The Danish anchor seine is different compared to bottom trawls as it operates two long seine ropes to herd fish together in the fishing area, which challenges existing gear monitoring sensors applied in the bottom trawl fisheries. To increase the knowledge on Danish anchor seining and its effects on the marine environment, substantial developments in existing methods were made that allowed for detailed data collections under commercial conditions. This study has been able to describe the fishing process of a Danish anchor seine. It also showed that fish enter the seine net very late, that the experimentally observed impacts of the gear on the seabed seem to be low and that unaccounted selectivity occurs in the seine net. Finally, a comparison of the selectivity characteristics and fishing profiles between Danish anchor seines and bottom trawls as most important fishing gear worldwide has been possible. This present Ph.D. thesis consists of a synopsis and four supporting papers.

Paper 1 presents the results of a set of sea trials, where various sensors and cameras were used to observe the fishing overall operation of Danish anchor seining, to track fish moving into the seine net, and to assess whether the process can be efficiently conducted without the use of monitoring devices. The results indicated that the operation of the seine ropes and net is relatively well conducted, in relation to maximize efficiency, without the guidance of these surveillance devices. Furthermore, the results showed that observed disturbances of the seabed are lower for Danish anchor seining when compared to those for bottom trawlers.

Another set of sea trials was carried out to estimate selectivity of a commercial Danish anchor seine codend for target species of fish (Paper 2). The estimation of selectivity parameters and curves showed that selectivity was often best described by the combination of two or three logistic models, which is indicative of a multiple selection

process. Although this is different to bottom trawl studies, where simple logistic models are usually used to describe selectivity, estimates of the selection range as codend selectivity parameter were similar for both fishing gears.

Paper 3 investigated impacts of a Danish anchor seine on fish that escape from the net, before they reach the codend, by attaching small mesh collecting bags to different parts of the gear. The results indicate that only considering the codend catch ignores substantial interactions between net and several species – especially the invertebrates. Most fish escaped through the lower panel in the aft part of the gear, and many of the invertebrates also escaped from the lower panels in the front part of the gear. Visible damages to the invertebrates were recorded to indicate the nature of their interactions with the netting and potential undocumented post release mortality. The observed damages to the captured organisms were low.

Paper 4 used data from observer trips to compare Danish anchor seiners and bottom trawlers in terms of fishing characteristics and catches of economic species. The main outcome of this approach was that Danish anchor seining is an efficient method to catch plaice (*Pleuronectes platessa*) and other flatfish, but is restricted in terms of fishing areas. Contrarily, bottom trawlers fished in more diverse areas and targeted more species. Differences in the ratio of captured fish below minimum size between both gear types and mesh sizes were small. However, additional seasonal and local factors and random effects of vessel and trip played an important role in determining the catches.

# 1. What is Danish anchor seining?

## 1.1 History

More than 150 years ago, back in 1848, the Danish fisherman Jens Væver started fishing for flatfish using a net to which two long ropes were attached (Thomson, 1981). He called the fishing gear “Snurrevod”, which literally means “spinning seine”. During the fishing process, these ropes were laid out encircling an area where the fishermen expected fish to be and were then retrieved by man power. Since around 1900, winches began to be used to facilitate the process. During retrieval, the ropes are moving in a twirling manner over the seafloor, creating a dust cloud, which scares and herds the fish into the middle of the fishing area. At the end of the fishing process, the fish enter the seine net and accumulate in the codend. As Danish seiners are anchored during the retrieval phase of the fishing process, another common name for this fishing technique is “Anchor seining”. In the following text, Danish anchor seining will be referred to as Danish seining.

## 1.2 The fishing process

In principle, the process of Danish seining consists of three main phases: the setting phase (Figure 1A-C), the fish collecting phase (Figure 1D-E) and the closing phase (Figure 1 F).

First, the vessel sets the starting point by dropping the anchor, which is attached to a set of marker buoys. Afterwards the vessel starts encircling the fishing area by laying out the first leaded rope (Figure 1A), which can be up to 4000 m long. Usually, the ropes are made of connected rope pieces, so called “coils” (1 coil  $\approx$  220 m), which, in the past, were used and stored as single coils and only connected for the fishing process (Thomson, 1981). As soon as the end of the first rope is approached, it is attached to one wing tip of the seine net. A second leaded rope is then connected to the other wing tip of the seine and laid out afterwards (Figure 1B) towards the starting point in a shape that ends up in a triangle (Figure 1C). Afterwards, both seine ropes are retrieved and fish are herded in front of the seine net (Figure 1D, Figure 1E) to finally collect them (Figure 1F). A major modification of Danish seining in Denmark is the way of setting out the seine ropes. Instead of returning to the anchor when the second rope is set out completely, its deployment starts by laying it out in a straight line away from the seine

net and only the last part of the rope is directed towards the anchor (Figure 1C). When the rope is set out completely, the end is attached to the aft of the vessel and dragged slowly over the sea bed, which increases the size of the fished area. In Danish, this technique is called “slæb på tampen” which means “drag on the rope”. It is particularly common when fishing for plaice (*Pleuronectes platessa*), which is by far the most important target species in the Danish seine fishery in Denmark in terms of volume and economy. Periodically or locally, however, Danish seiners also target other flatfish species like witch flounder (*Glyptocephalus cynoglossus*) or roundfish species like cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) or hake (*Merluccius merluccius*).

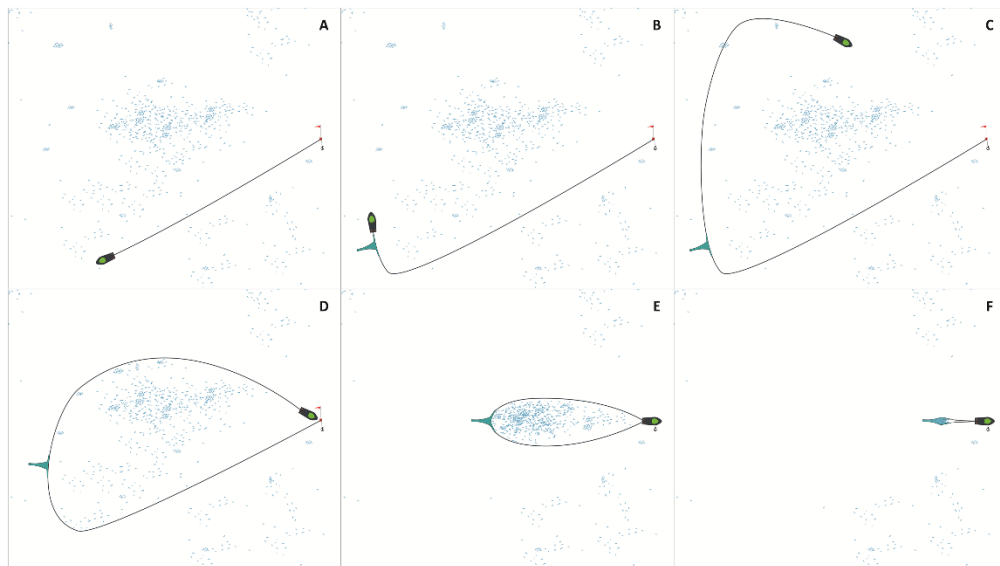


Figure 1: Process description of Danish seining (unmodified from **Paper 1**). A-C: Setting phase. D and E: Fish collecting phase. F: Closing phase.

### 1.3 Demersal seining in other countries

Due to its efficiency, Danish seining became one of the most important fishing gears used in Denmark in the first half of the 20th century (Thomson, 1981) and, at the same time, other foreign fishermen became interested in this innovative way of fishing. They introduced it to their home countries and adopted it to local conditions and behaviours. Scottish fishermen, for instance, started to fish without an anchor. Besides one myth that this was done to leave the fishing area faster in case of a fishing control by the authorities (Thomson, 1981), it enabled the vessels to move forward during hauling and



thus, to cover larger areas and to tow the gear faster over the sea bed. Common names for this modified technique are “Scottish seining”, ‘Fly-dragging’ or ‘Fly-shooting’. This is also the common way of demersal seining in Norway nowadays (although several people refer to demersal seining in Norway as “Danish seining”). The seine ropes used by Scottish seiners (diameter ~25-40 mm) are thicker than those used by Danish seiners (diameter ~20-30 mm). Two reasons for this are the often rougher sea floors where Scottish seines are used (Eigaard et al., 2016a) and the higher retrieval speeds of Scottish seines (Eigaard et al., 2016a). For this reason, also the ground gear is usually more robust for Scottish seines relative to the Danish seines. Another difference between both gears is the number of used coils, i.e. the length of the seine ropes. As Scottish seines tow the gear during retrieval, they usually use shorter ropes (8-10 coils) than Danish seiners (10-15 coils).

Furthermore, “pair seining” has been invented in Scotland, which gives remarkable increases in the hourly swept area but requires two vessels (Galbraith et al., 2004). In this process, the net is set out first with each vessel then setting out one rope. Thereafter, both vessels tow the gear, get closer and finally come together to empty the codend. However, this technique is rather similar to pair trawling.

### ***1.4 Legal considerations***

A common detail for the classification of fishing gears is based on how the fish or shellfish come into contact with the gear. A passive gear attracts fish using bait (e.g., longlines, baited fish pots) or depends upon the fish swimming into it (e.g., gill nets, traps). Contrarily, active gears herd or surround the targeted fish. Examples are trawls (e.g., beam trawls, demersal trawls or pelagic trawls) and dredges, but also seine nets (beach seines, purse seines and demersal seines). Although there are pronounced differences between the methods of Danish seining and bottom trawling (e.g., no trawl doors in seines) and between Danish seines and Scottish seines (e.g., Scottish seines are not anchored), all three gear types are classified to the same gear category by the European Union (EU) fishery legislation (Council Regulation (EC) 850/98). Therefore, all three gears follow the same technical legislation regarding, for instance, mesh size regulations or the use of selective devices.

### 1.5 Recent developments in the Danish seine fleet

The general decrease of fishing vessels in the world (FAO, 2014) and in Denmark (Ulrich & Andersen 2004) can also be seen in the fleet of Danish seiners in Denmark which decreased from 287 vessels in 1987 to 26 vessels in 2016 (Figure 2; logbook register, Ministry of Environment and Food of Denmark). In addition to this substantial reduction, many Danish seiners have been superseded by trawlers over the last decades (Ulrich and Andersen, 2004) and some vessels operate as combi (or multi-purpose) vessels that can fish with both seines and trawls. A likely reason for the decreasing numbers of Danish seiners may be the higher work-load of Danish seining in comparison to bottom trawling (Suuronen et al., 2012) or the fact that bottom trawlers are more flexible in the choice of fishing locations and can target a higher diversity of species (**Paper 4**). Nevertheless, Danish seining still constitutes an important part of the fisheries in Denmark and also many other countries all over the world (ICES, 2010).

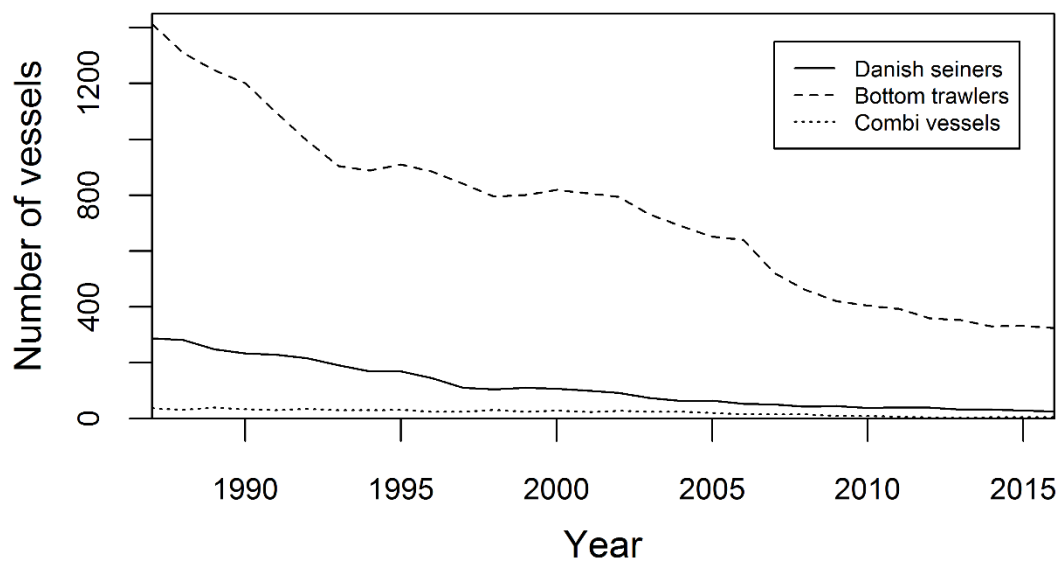


Figure 2: Development of Danish seiners, bottom trawlers and combi vessels from 1987 to 2016 (logbook register, Ministry of Environment and Food of Denmark). Combi (Multi-purpose) vessels are capable of using both seines and bottom trawls.

Despite the decrease of vessels practicing Danish seining, recently, there has been renewed interest in this way of fishing. This may be caused by the several advantages the fishing method offers compared to bottom trawling. Ecological advantages are hereby important because consumer requests for sustainable products have been

increasing in recent years (Jaffry et al., 2016). These include relatively low impacts on the ecosystems of the sea floor (Walsh and Winger, 2011; Suuronen et al., 2012; Eigaard et al., 2016a) because relatively light ground gear is used, and trawl doors, which are responsible for a substantial part of seabed disturbance from bottom trawls (Jennings et al., 2001b; Gilkinson et al., 1998), are not necessary. This needlessness of trawl doors, the relatively light ground gear constructions and the fact that only winch power is used during the retrieval process, lead to a lower fuel consumption than for bottom trawls (Thrane, 2004). This is of interest from both an economic and ecological point of view as it means lower fuel costs and emissions of CO<sub>2</sub>. Furthermore, catches of Danish seiners are known to be of high quality (Walsh and Winger, 2011; Suuronen et al., 2012), which is also the reason demersal seining is the preferred way of catching fish for catch-based aquaculture (Dreyer et al., 2008).

### ***1.6 The aim of the project***

Despite the use of Danish seines all around the world and the increasing interest in the gear, the level of knowledge about Danish seining is low. However, there is a general need for a detailed understanding of this fishing method, and its effects on the environment, to correctly group it legislatively and to inform current management strategies – like the European Common Fisheries Policy (CFP). Instead of focusing on specific sectors, current strategies are directed towards the ecosystem-based approach, which aims at minimizing negative impacts of fishing activities on the entire marine ecosystem (Regulation (EC) No 1380/2013). This requires an assessment of the negative effects that individual fishing gears have on the different parts of the marine ecosystem, which will reveal potential opportunities for reducing their impact. As definition of “ecosystem effects” varies, we define it here as the sum of all direct and indirect effects on species of all trophic levels in the marine habitat including target and non-target species (Gislason, 2003; Jennings and Kaiser, 1998). Most of the sparsely available information on the effects of Danish anchor seining on the ecosystem, like selectivity estimates, levels of discards or interactions with the sea bed, are based on assumptions that were not proven by scientific studies. In order to address these points, and to increase the basic understanding of Danish seining and its effects on the ecosystem, the present study investigated methods and tools to gather these missing information. Focus was hereby on gear performance, catches, selectivity of all gear parts and seabed interactions. Within this Ph.D. thesis, these methods are described,

their suitability is evaluated, and the corresponding results are presented and discussed in relation to bottom trawling, which is currently the most important demersal fishing method worldwide (Watson et al., 2006).

## 2. Technical description of the fishing process

### 2.1 *State of knowledge*

A fundamental understanding of a fishing process provides the basis for modifying, adapting and improving it. Contrary to bottom trawls, and other demersal fishing methods, Danish seining is, however, carried out in blind, i.e. the fishermen do not use any monitoring devices on their gear. The most likely reason for this is the considerable distance between vessel and the seine net, which does not allow the use of available acoustic gear monitoring devices. Nevertheless, the fishermen have clear expectations of the process and the behavior of the seine net and the seine ropes during the different stages of the fishing process. These expectations provide the basis for the fishermen's behavior on how to set and operate the gear, e.g. in which pattern the ropes should be laid out, or when rope hauling speed should be increased during the retrieval process.

The number of scientific publications describing the operational performance of demersal seines is limited to only few. In the late 1980s, Galbraith and Kynoch (1990) used various sensors to conduct Scottish seine performance trials. Although they were able to estimate the size of the fished area, based on the length of the seine ropes, they were not able to adequately describe the behavior of seine net and seine ropes during all stages of the fishing process and all results are restricted to Scottish seining. A more theoretical study by Eigaard et al. (2016a) compared the impacts of different fishing gears on the sea bed using Global Positioning System (GPS) loggers onboard Danish seiners to estimate the size of the area being affected.

### 2.2 *The current approach*

Within the study described in **Paper 1**, a surface connection system has been invented to attach GPS loggers to the wing tips of a Danish seine and to various positions on the ropes. Furthermore, depth loggers were mounted at the head and ground rope and tension sensors were installed between the seine ropes and net. The combined information about rope and net behavior (e.g., movement, wing spread, net height), and forces acting on both sides of the gear (Figure 3), gave a detailed description of the Danish seine fishing operation. Furthermore, it was possible to assess the potential to optimize this process, and its impact on the sea bed in relation to bottom trawls and previous estimates for Danish seines.

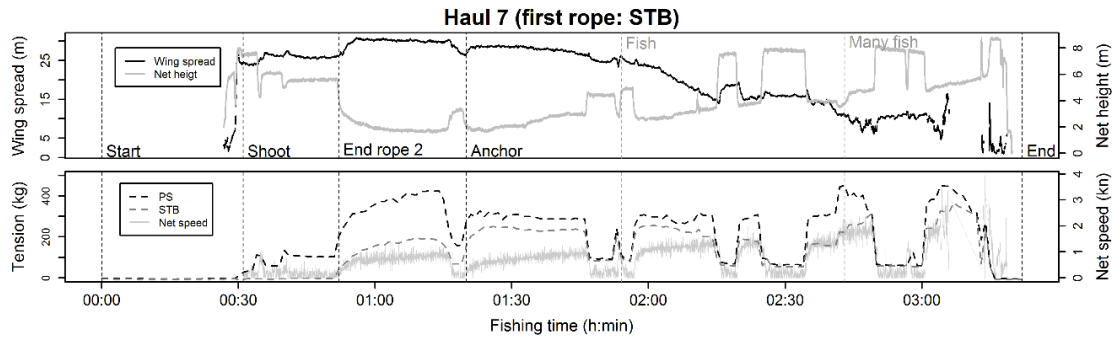


Figure 3: Parameters describing the performance of a Danish Seine (wing spread, net height, tension, net speed) including time information about fishing process (hours:minutes) and fish observations representatively for haul 7 of the trials 2015. Unmodified from **Paper 1**.

### 2.2.1 Behavior of seine net and ropes

The initial hauling patterns were relatively asymmetrical between rope 1 and 2, but got more symmetrical when they came closer during the later fishing process (**Paper 1**). The initial asymmetry was mainly attributed to the fact that rope 2 is laid out away from the anchor and then towed to it (“slæb på tampen” procedure; see 1.2 The fishing process).

The global geometry of the seine net changed considerably during the fishing process. Immediately after setting the seine net, it was overspread until the vessel was back at the anchor, i.e. the wing spread was very high and the net height very low (Figure 3, **Paper 1**). Only when retrieval of both ropes began, and both wings were towed equally, did the net started to obtain its intended shape. The spread decreased and the net height increased until the end of the fishing process (Figure 3, **Paper 1**). The ground rope started to lift from the sea bed as soon as wing spreads got <10 m.

The tension between seine net and seine ropes was, particularly in the beginning, stronger on the second rope, which was towed back to the anchor, but harmonized during the fishing process (Figure 3, **Paper 1**).

All this information, characterizing the fishing process, can be found in form of animations of each haul in the supplementary material of **Paper 1**. A comparison of the present results to those obtained for Scottish seining indicated certain similarities in terms of net shape and forces acting on the gear. For instance, a constantly changing net shape has also been observed for Scottish seines (Galbraith and Kynoch, 1990). Initial asymmetry between geometry and forces between both sides, and the subsequent

equalization as the haul progressed, was also observed for Scottish seines (Galbraith and Kynoch, 1990). Differences in asymmetry are, however, smaller than in Danish seining, as the “slæb på tampen” causes a much more pronounced initial asymmetry between both sides.

### **2.2.2 Catching process and fishermen’s behavior**

Fish spent relatively brief periods of time in the seine net as they always entered it within a relatively short period within the last quarter of the fishing process. This is a likely explanation for the high quality of catches by Danish seines (Dreyer et al., 2008; Suuronen et al., 2012). The part of the study, which described the gear performance, showed that net geometry varied considerably in the period when fish entered the seine net. It is, however, important that the seine net is in its intended shape during the main catching phase as it is otherwise likely that the seine net would not catch all fish that have been herded by the seine ropes. Furthermore, it is important that the ground rope stays at the sea bed at this time to prevent fish from swimming underneath. In order to adapt the fishing process to the entering of fish, the fishermen have basically one tool, which is the adjustment of the retrieval speed. The general pattern they follow is to start with low winch speeds in the beginning of the retrieval process (~1.5 kn) and to increase it stepwise during the later stages. It is increased when about half of the rope is retrieved, when ca. four coils were left, and again to a maximum of ~4.6 kn when the ropes touch each other (when ca. two coils were left to retrieve). This last speed-up is the point in time when fishermen expect the ground rope of the seine net to lift off the sea floor, i.e. when fish could swim beneath it. Video recordings revealed that the majority of fish generally entered the codend before the ground rope lifted off the seabed and that increases in retrieval speed could have been set only slightly different to minimize the risk of premature lifting of the ground rope (**Paper 1**). This showed that the fishermen are skilled in adapting the process to the different conditions without the use of monitoring devices to inform these decisions.

### **2.2.3 Area swept by seine net and seine ropes**

Eigaard et al. (2016a) derived a formula to calculate the swept area by Danish seines in order to estimate the gear’s footprint. Applying this formula to the measurements of the study described in **Paper 1**, however, would underestimate the swept area (calculated after Eigaard et al. (2016a): 4.1 km<sup>2</sup>, measured: 4.1–5.5 km<sup>2</sup>). A likely reason for this difference may again be the way of laying out the ropes. Furthermore, the mean value

for the hourly swept area of 1.0 km<sup>2</sup> by Eigaard et al. (2016a) seemed to be too small. Values estimated within the study of **Paper 1** ranged from 1.1 to 1.6 km<sup>2</sup> and were similar to estimates for Scottish seines, which range from 1.2 (when using 14 coils of rope; Galbraith and Kynoch, 1990) up to 1.6 km<sup>2</sup> (Eigaard et al., 2016a). To separate the footprint of Danish seines by ropes and net, Eigaard et al. (2016a) assumed that the area which is covered by the ground gear represents about 10% of the fishing area. The results of **Paper 1** indicated, however, that this is likely overestimated as only around 1% of the fishing area is swept by the seine net.

### ***2.3 Comparison to bottom trawls***

In contrast to Danish seines, commercial bottom trawls are usually equipped with different sensors to monitor the gear and several studies investigated trawl performance during the fishing process (e.g., Carrothers, 1980; Bertrand et al., 2002; Priour and de la Prada, 2015). Bottom trawlers use trawl doors to spread the net and seiners operate very long ropes. This considerable difference causes net geometry to differ between both gears. Although trawls show some variation in the shooting phase, net height and wing spread harmonize relatively quickly and stay more or less constant until the gear is retrieved in the final stage of the fishing process (Priour and de la Prada, 2015; Bertrand et al., 2002). As described above, this is not the case for Danish seines. Linked to these aspects is also the entering of fish into the net. Contrary to trawls, most fish enter the seine net within a limited period during the later stages of the fishing process (**Paper 1**).

Furthermore, the towing speed itself and the source determining it differ between the gears. Danish seines are retrieved only by using winches (Scottish seines by winches and vessel) and the towing is comparatively low, ranging from ~1.5 kn in the beginning to about 3.5 kn in the final stage of the hauling process (Eigaard et al., 2016a). Bottom trawls are towed continuously fast by the vessel itself, with a speed of up to 4 kn (Eigaard et al., 2016a). In combination with a usually heavier ground gear, this explains the lower tension values between the seine net and the seine ropes in comparison to bridle tension for a bottom trawl. Average estimates of **Paper 1** were less than half of what has been reported for similar sized bottom trawls (Priour and de la Prada, 2015). Another difference between the gears is the are swept hourly. Estimates for conventional bottom trawls targeting fish range from 0.4 (Galbraith and Kynoch, 1990)



up to 0.8 km<sup>2</sup> (Eigaard et al., 2016b). Values for Danish seines range from 1.0 (Eigaard et al., 2016a) up to 1.3 km<sup>2</sup> (**Paper 1**), which indicates Danish seiners to cover a larger area in the same time. Nevertheless, Danish seiners are less time flexible than bottom trawlers, because they have to finish the entire fishing procedure before they can retrieve the gear. This can be disadvantageous if, for instance, the catch is getting too big or weather changes quickly.



### 3. Codend selectivity of Danish seines

The codend is the part of towed fishing gears, where the main selectivity occurs for most fish (Wileman et al., 1996). Besides Herrmann et al. (2016a), **Paper 2** is one of few studies that investigated codend selectivity for Danish seines and is, to my knowledge, the only one that estimated selectivity curves for a codend that is commercially used today.

#### 3.1 Cover development

In order to carry out the trials, a cover needed to be developed based on the principles of the conventional codend cover for trawls (Wileman et al., 1996). An adaption to Danish seining by using a combination of floats, weights and a horizontal pole had been necessary because a Danish seine does not move as uniform as a trawl. Keeping the cover in a sufficient distance from the codend was, however, essential to avoid a potential masking effect that can occur when the cover comes in contact with the meshes of the codend (Madsen and Holst, 2002). Masking could prevent individuals from escaping from the codend, which could bias the selectivity analyses.

#### 3.2 Selectivity parameters

Selectivity curves and parameters including L50 (length at which 50% of the fish are retained) and SR (selection range; L75–L25) were estimated for four species (**Paper 2**); including plaice as the most important species in the Danish seine fishery. The selectivity curve of plaice (Figure 4) showed that some fish below current minimum landing size (MLS) were retained by the Danish seine, although the used mesh size was relatively large (**Paper 2**). A likely explanation for this is the short time in which large amounts of fish enter the gear (**Paper 1**), i.e. the contact likelihood of the fish, and thus their chance to escape may be reduced.

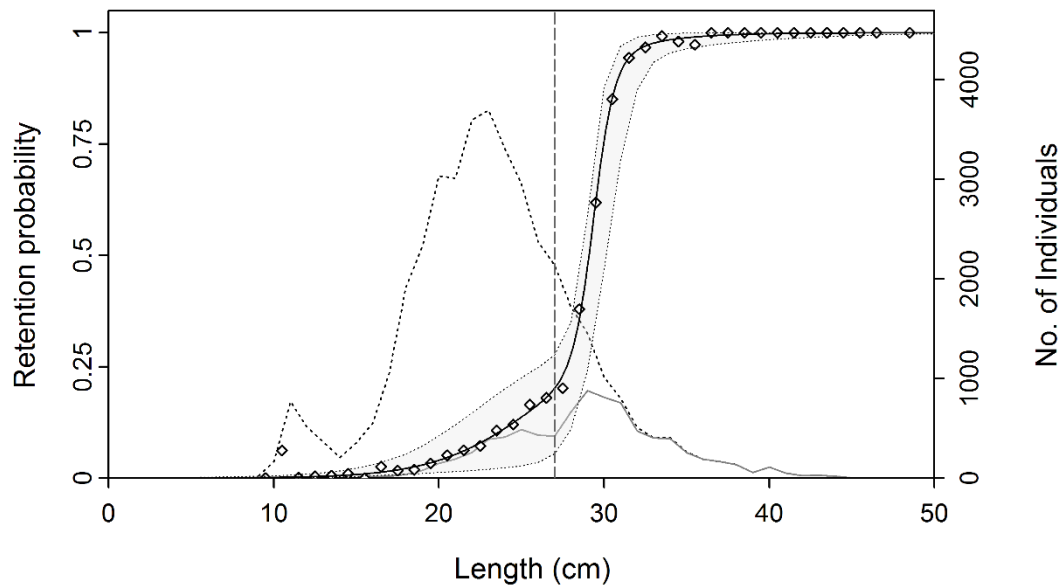


Figure 4: Selectivity curve for plaice including 95% confidence intervals (grey shaded areas), length-specific retention rates (white diamonds), current species-specific MLS (vertical stippled line), and length distributions (stippled line: total; solid line: codend). Modified from *Paper 2*.

Plaice and dab (*Limanda limanda*) were the two species with the strongest data in the analysis. Both could be best described by a model that combined two or three logistic functions (**Paper 2**). So far, such models have been used in trawl studies that separated the fishing process into towing and haul-back phase (Herrmann et al., 2013a), or when using selective devices (Kvamme and Isaksen, 2004; Sistiaga et al., 2010; Herrmann et al., 2013b). In short, these were studies that considered the selectivity process in trawling to consist of two or more processes. The considerably dynamic geometry of a Danish seine during the fishing process, and thus in the netting characteristics (**Paper 1**), likely affects selectivity characteristics of a Danish seine in a similar way and could result in multiple selection processes. Another important point is the moment during retrieval when the seine net needs to be stopped in order to be detached from the ropes and attached to the net drum for final retrieval. This stop leads to a complete standstill of the gear, which could give slack regions in the netting. This change from stiff to slack mesh, in combination with lively activity of the fish as they enter the seine net in a relatively short period in the end of the fishing process (**Paper 1**), may explain the observed multiple selection in the Danish seine fishing process.

As the results and selectivity parameter estimates of multiple selection models may differ from estimates by the traditionally used logistic function (Herrmann et al., 2016b), these more complex models should be considered in all future studies aiming to describe Danish seine selectivity.

### ***3.3 Comparison to bottom trawls***

Danish seiners do not use trawl doors to spread the net as bottom trawlers do (von Brandt, 2005) and are anchored during the entire retrieval process. Additionally, the gears show several differences in net performance (see 2.3 Comparison to bottom trawls), which make differences in the selection processes of both gears likely.

Contrary to demersal seines, a lot of studies investigated codend selectivity in bottom trawls (Graham and Kynoch, 2001; Frandsen et al., 2010a; Fryer et al., 2016), where the logistic function is the usual way to model selectivity of trawls. Contrary to the more complex models tested within **Paper 2**, the logistic model considers the selection to consist of only one process, which does not change during the fishing process. Since different codend selectivity studies used codends with different mesh sizes, the selection factor ( $SF = L50$  divided by mesh size) has been calculated in **Paper 2** as a suitable measure allowing for a comparison between the studies. For the few species where a comparison was possible, we found SF values of roundfish to be slightly higher for Danish seines. Values for flatfish were comparable for both gears (**Paper 2**).

One aspect that should be highlighted once more at this point is the relatively short period in the late retrieval process when fish enter the seine net (**Paper 1**). As most selective devices were designed for trawls where fish enter the net continuously over the whole fishing process, such devices may work differently in demersal seines. This is an important aspect because of the legal grouping of demersal seines and trawls in the same category (Council Regulation (EC) 850/98), meaning that both have to follow the same regulations in terms of mesh sizes and the use of selective devices.



## 4. Interactions of fish and invertebrates with other parts of the Danish seine

Although the codend is where the main selection of fish occurs in towed fishing gears (Wileman et al., 1996), previous studies have reported the escape of different invertebrate species from the forward parts of different types of towed fishing gears (Hillis and Earley, 1982; Krag et al., 2014a; Polet, 2000). This implies that usual selectivity or survival studies, which normally focus only on the codend catch, may ignore potential interactions of fishing gears with animals that do not reach the codend, but are affected by the gear. Estimating the magnitude of these potential interactions of organisms with different fishing gears, including Danish seines, is important in elucidating the full range of impacts these fishing gears have on the marine environment and informs many current management strategies, such as the EU CFP (Zhou et al., 2010). These new more complex strategies aim at considering all species of the ecosystem, which is different to former management regimes that focused mostly on the few species of commercial importance. However, this approach is appropriate because different species play different roles in the marine ecosystem ranging from being prey for valuable fish species to playing important key functions such as supporting roles in matter cycles or increasing habitat complexity, and thus encouraging survivorship and recruitment of juveniles of commercial species (Kaiser et al., 1998).

Within the study described in **Paper 3**, the seine net was strategically divided into 12 sections to which each a small meshed bag was attached allowing to collect escaping animals throughout the entire seine net. Combined with damage levels, which were assessed for all caught invertebrates, this study clearly indicated that there is an unaccounted interaction between animals and gear parts that cannot be estimated based on the codend catch. The obtained catch information indicated different behavior patterns between the caught species.

In order to visually evaluate animal behavior in relation to the gear, underwater video cameras were attached to different parts of the seine net (**Paper 1** and **Paper 2**), or to self-invented observation platforms that were dropped in the fishing area to record how fish behave in relation to the seine ropes (**Paper 1**).

## 4.1 Fish

The majority of benthic fish species (e.g., plaice and dab) escaped through the lower panel in the aft part of the gear where pelagic species like herring (*Clupea harengus*) and sprat (*Sprattus sprattus*), escaped solely through meshes in the upper panel in the aft part of the gear (**Paper 3**). Such species-specific behavioral differences are of importance for potential gear modifications to improve the seine's selectivity of unwanted species or sizes, as demonstrated for trawls (Thomsen, 1993; Krag et al., 2014b; Krag et al., 2015).

The late escape, and the fact that the asymmetry of the fishing process was not reflected in the escape patterns, can likely be explained by the fish behavior. Contrary to invertebrates, most fish are very motile organisms and the fish are, due to the specific gear characteristics and the relatively low retrieval speed (**Paper 1**, see 2.2.2 Catching process and fishermen's behavior), likely in good condition when they enter the gear. As fish avoid contact with the netting of a fishing gear (Glass et al., 1993; Glass and Wardle, 1995), they follow the path of the net until they reach the tapered net parts where they get condensed, start to feel stressed and start trying to escape.

The video recordings in **Paper 1** and **Paper 2** showed that most fish entered the seine net very late in the fishing process. Although a few fish could also be seen at earlier stages, the majority of the catch entered the seine net within the last quarter of the fishing process (**Paper 1**), which can be explained by the way Danish seines herd the fish (Figure 1). Moreover, the anchored cameras revealed that flatfish remained much closer to the sea bed than roundfish did during the herding process, and showed that a distance of several meters between fish and seine ropes was enough to scare fish up.

## 4.2 Invertebrates

Catches of invertebrates in the collecting bags in relation to the codend catch were relatively high (**Paper 3**), indicating again that there is an interaction between organisms and seine net that is ignored by usual selectivity studies. Contrary to fish, high escape rates of invertebrates were also found in the collecting bags at the lower panels of the wing sections (**Paper 3**), especially in bags which were attached to the side that got dragged back to the anchor ("slæb på tampen" procedure; see 1.2 The fishing process) and, in the process, swept a larger area containing more animals. This

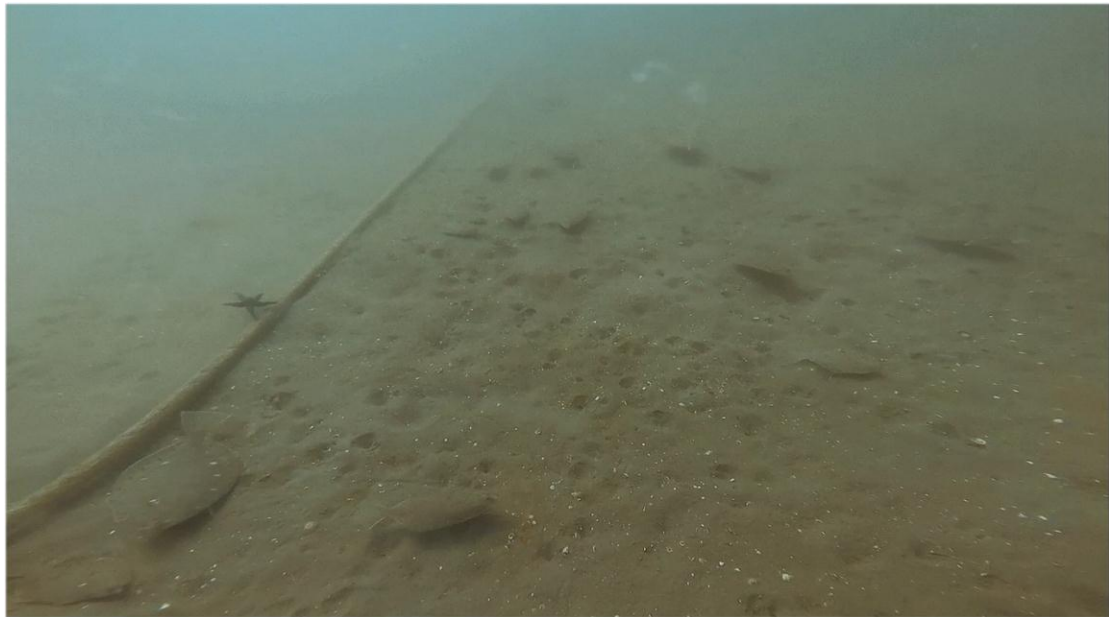


indicated that escape behaviors of invertebrates, and thus also the vertical position where they can escape, is mainly determined passively, which is probably due to their limited swimming capabilities compared to fish. As invertebrates are therefore expected to roll more passively along the lower netting, resulting in multiple contacts with the meshes from the ground gear and backwards to the codend, it can be concluded that selectivity for invertebrates in Danish seines is different from fish, which escape to large extents through meshes in the codend (Wileman et al., 1996).

Damage to the collected invertebrates was found to be relatively small (**Paper 3**), which was likely due to their robust exoskeleton or shells. Differences between the gear parts indicated a tendency of higher damage levels in the aft parts of the gear, which are most likely caused by more mechanical interaction with the netting due to a longer travel inside the netting. This means that lower damage levels can be expected for animals released earlier in the process.

#### ***4.3 Comparison to bottom trawls***

Since Danish seines and trawls are gears that are operated differently, differences in the behavior of fish interacting with the gear are likely. A study by Ryer (2008), for instance, investigated flatfish behavior in relation to trawl sweeps, but found fish to not react to the trawl sweeps until they are less than one meter away. Contrarily, we observed fish lying on the sea bed to react to the seine ropes several meters away (Figure 5). A potential explanation for this may be the diameter of the seine ropes as they are thicker and create a larger dust cloud. This may induce a flight reaction earlier than the sweeps of trawls do.



*Figure 5: Fish herded by a seine rope.*

Furthermore, the moment and the duration when fish enter the net and the codend is a major difference between trawls and seines. Seine nets are entered within a narrow time window at the end of the fishing process (**Paper 1**, **Paper 2**), whereas trawl nets are entered continuously over the whole fishing process. As mentioned above (see 3.3 Comparison to bottom trawls), this fact should be kept in mind as it results in a relatively prompt filling of the codend, which may cause a faster blocking of the meshes with larger catches, and could therefore affect the selectivity and the correct functioning of selective devices.

Behavior of animals inside the seine net was similar to what has been observed for bottom trawls. For example, tendencies of flatfish and invertebrates to escape downwards (**Paper 3**) has also been reported for bottom trawls (Frandsen et al., 2010b). Contrarily, interactions of invertebrates with the gear and linked damages to the animals, are likely more pronounced in bottom trawling, especially *Nephrops*-directed trawling, because the towing durations is longer than for Danish seiners (**Paper 4**) and smaller mesh sizes are used (Krag et al., 2008) which increases the netting contact with the organisms.

## 5. Interaction with the sea bed

Demersal fishing alters the habitats of benthic invertebrates and thus affects the functioning of their communities (Reiss et al., 2009). Experimentally validated knowledge about impacts of Danish seines on the sea bed is, however, missing. Therefore, we attached cameras to self-invented observation platforms (**Paper 1**), which maintained their positions on the sea bed whilst allowing the ropes to pass underneath. These were placed in the fishing area before we conducted the commercial Danish seining. Except for slight smoothening effects, the recordings did not show any pronounced changes in the bottom after the seine ropes passed by (Figure 6), which is likely because of the relatively light ground gear, slow retrieval speed and flat and sandy fishing grounds (**Paper 1**). Dust clouds caused by the seine ropes completely disappeared within two minutes.



*Figure 6: Seine rope interactions with the sea bed. A. Sea bed immediately before rope is passing by. B. Sea bed as the rope passes by. C. Sea bed one minute after rope has passed by.*

These observations support the assumptions of several previous studies which expected effects of Danish seines on the sea bed to be minor (ICES, 2006; Suuronen et al., 2012), but did not allow for a quantitative assessment of the interactions. It needs to be mentioned that the magnitude of impacts fishing gears have on the sea bed depends to a large extent on its structure. Danish seiners fish usually on flat and meagre sand bottoms to not damage their gear by, for instance, entangling ropes in obstacles like boulders (Fuller and Cameron, 1998).

### ***5.1 Comparison to bottom trawls***

Several studies investigated impacts of bottom trawls on the sea bed and the corresponding short- (Kaiser et al., 2006; O'Neill and Summerbell, 2011) and long-term effects (Kaiser et al., 2006; Kaiser et al., 2002) on the environment. Eigaard et al. (2016a) compared mechanical impacts on the seabed of various demersal gears including (Danish and Scottish) seines and bottom trawls, where they assumed that seine ropes had similar effects to trawl sweeps and that the effects of the ground gear were also similar for both kinds of gears. At this point, attention should again be drawn to the differences in the gear constructions between Danish seines and bottom trawls. Danish seines use light ground gears as they usually fish on flat bottoms. Contrarily, the ground gear of bottom trawls is often a heavier to be able to fish on rougher sea floors (He and Winger, 2010), which could result in more pronounced interactions with the sea bed (e.g., due to higher penetration depths). The seine ropes are much longer than the trawl sweeps, but trawl sweeps are made of metal and the entire trawl is heavier than a Danish seine. This causes the tension between the trawl net and sweeps (Priour and de la Prada, 2015) to be remarkably higher than the tension between seine net and ropes (**Paper 1**). In combination with the generally higher speed of a trawl (see 2.3 Comparison to bottom trawls), it can be concluded that forces applied on the sea floor are lower for Danish seines than for bottom trawls. An aspect that further supports this finding is the absence of trawl doors in Danish seines, which are known to have considerable interactions with the sea bed (e.g., Gilkinson et al., 1998; Jennings et al., 2001a).

## 6. Fishing profile and catches of Danish seiners in comparison to bottom trawlers

Previous studies indicated differences between Danish seines and bottom trawls (Suuronen et al., 2012), e.g., in terms of the net performance during the fishing process (**Paper 1**), or in terms of codend selectivity characteristics (Herrmann et al., 2016a; **Paper 2**). To investigate if these differences are also reflected in the catches of both gears, an extensive observer dataset was used to compare the fishing profiles of both gears for a period of 16 years (**Paper 4**). Fishing profiles hereby refers not only to catches, but also to characteristics of the two fishing methods (e.g., haul duration or fishing depth). Such large-scale comparisons represent a comprehensive data source to determine, for instance, the probability of the fisheries to meet the objectives of the landing obligation (see 7.2 Landing obligation). Furthermore, it gives an indication of how suitable the legislative grouping of demersal seines and trawls is – a regulation that has been brought into question by fishermen and other stakeholders.

Higher flatfish catch rates for Danish seines, and a lower engine power giving lower fuel consumption, indicated Danish seining to be an energy efficient way of catching plaice and other flatfish (**Paper 4**). Trawlers fished in more diverse areas and in deeper waters, and they had higher catch rates of roundfish. Furthermore, trawlers targeted more species (main target: Norway lobster *Nephrops norvegicus*) than Danish seiners (**Paper 4**), which reflects their higher flexibility. There are two reasons for the differences in flexibility. Firstly, Danish seines are restricted to sandy flat fishing areas because of the long seine ropes and the rather light gear construction. Contrarily, bottom trawls are often constructed in a more robust way (He and Winger, 2010), which prevents the gear from damages due to rough sea bed structures. Therefore, trawlers are able to fish in more diverse areas. The second point is the difference in the fishing process. High speeds during the entire haul period allow trawlers to catch fast-swimming species that could easily escape from the rather slow Danish seine. Furthermore, Danish seining does not work efficiently for catching Norway lobster (**Paper 4**), which is most probably due to a low herding efficiency of this species by seine ropes.

Both gears caught fish below the minimum conservation reference size (MCRS) of several species mentioned within the landing obligation. These included plaice, which

is the most important species targeted by Danish seines, and Norway lobster, which is the most important target of trawls in the investigated area, where up to 50% of their catches were below MCRS (**Paper 4**). Differences between the gears and mesh sizes were small, but the conditions under which the gears were used were found to explain a lot of the deviance in catch rates and in the amount of fish below MCRS (**Paper 4**). Those included a high area aspect and a pronounced random effect of vessel or vessel's trip.

The results of this particular study, described in **Paper 4**, do not provide any clear indication to challenge the legal grouping of demersal seines with trawls based on their catches. However, there are two points to consider. Firstly, the considered factors may be linked, which possibly confounded, or even masked, effects of gears or mesh sizes in the analyses. Furthermore, catches of gears with a mesh size below 90 mm were excluded from the analyses to standardize the ranges of mesh sizes. Danish seiners usually utilize mesh sizes of 120 mm, but trawlers use smaller mesh sizes, which is necessary to catch Norway lobster (Krag et al., 2008). Today, 90 mm is normal for trawlers, but until changes in the regulation in 2005 (Council Regulation (EC) 27/2005), mesh sizes below 90 mm were common. This means that likely a big portion of small fish caught by trawlers was not considered within the study, which could have led to different results.

## **7. Final remarks and future work**

The present study was able to describe the global gear geometry of a Danish anchor seine during the fishing process. Furthermore, the results showed that

- fish enter the seine net very late,
- fishermen are able to conduct efficient Danish seining without using any gear monitoring equipment,
- the gear's impacts on the seabed are lower than for bottom trawlers,
- a substantial part of the gear's selectivity does not occur in the codend,
- codend selectivity characteristics are different to bottom trawls
- the Danish anchor seine is a fishing gear that is highly specialized on catching flatfish.

Additionally, the results provide the basis for future studies on Danish seining and are important in terms of several management aspects.

### **7.1 NATURA 2000**

The low level of sea bed interactions should be borne in mind when discussing future management of Natura 2000 areas (e.g., “Skagerrak and Skagens Gren”, Habitats Directive 92/43/EEC), because they include substantial parts of the study areas (Skagerrak and Kattegat) and protection of the sea bed (including bubble reefs and other fragile structures) is one of the main aims of the Natura 2000 plan. Although all demersal fishing affects the sea bed and the benthic communities to some extent (Reiss et al., 2009), different levels of impairment of different fishing gears and potential exemptions for “low impact gears”, such as the Danish seine, should be considered. The Dutch government, for instance, intends to protect 10-15% of the Dutch continental shelf from bottom disturbance by closing Natura 2000 areas in the North Sea to different bottom trawl fishing methods (IenM and EZ, 2012), whilst continuing to allow methods with lower impacts on the sea bed – such as Danish anchor seining. Another example is Norway, giving exclusive rights to demersal seiners in coastal areas (Regulations governing the sea-fishing activities J-125-2016 §15, §53; Norwegian Directorate of Fisheries).

## 7.2 Landing obligation

A significant proportion of marine catches is discarded (Kelleher, 2005), i.e. is returned to the sea (FAO, 1996). This happens for several reasons, like quota restrictions or high-grading (Kelleher, 2005; Feekings et al., 2012; Catchpole et al., 2013), but is generally considered to constitute a suboptimal use of fishery resources. Maria Damanaki, the previous European Union Commissioner for Maritime Affairs and Fisheries, expressed it as follows: *“I consider discarding of fish unethical, a waste of natural resources and a waste of fishermen's effort”*.

With the introduction of the landing obligation, the EU aims at eliminating discards. As it constitutes a main part of the new CFP (Council Regulation (EU) 1380/2013; Eliassen, 2014; de Vos et al., 2016), it represents one of the main topics in current management discussions about EU fisheries. The implication of the landing obligation started in 2015 and is planned to be expanded on a fishery by fishery basis until 2019 (Council Regulation (EU) 2016/72). It applies to all species “which define the fisheries”, i.e. species subject to catch limits, and introduces MCRSs, which are usually equal to current MLSs. Fish below this size are not allowed to be sold for direct human consumption (Regulation (EU) No 1380/2013 of the European Parliament and of the Council), but are counted against quota. This means that earnings for those fish will be less than for fish above MCRS. As the results in **Paper 4** indicated, both bottom trawlers and Danish seiners will be affected by the landing obligation because both caught fish below MCRS. However, differences between the gears are likely small, although catch rates of roundfish and flatfish differed between the gears.

Additionally to these economic effects, the implementation of the landing obligation likely also affects the ecosystem because discards have direct effects on scavenging seabirds (Votier et al., 2013), mammals (Hill and Wassenberg, 1990; Couperus, 1994), fish (Oro et al., 2013) and benthic invertebrates (Kaiser and Hiddink, 2007; Groenewold and Fonds, 2013), but also indirect effects on the entire food web (Heath et al., 2014). Therefore, Fondo et al. (2015) recommended a slow and gradual introduction of the landing obligation, in order to allow scavenging species that experienced provision of these subsidies over decades to adapt to this prospective missing source of food. Hereby, the level of reduction depends also on how strict fishermen stick to the rules. Several studies concluded a high risk of ongoing discarding of listed species in case controls are not carried out or fines are not set appropriately (Sardà et al., 2015). A



prediction of the fishermen's behavior is, however, difficult and likewise the amount of "missing discards", which makes conclusive statements impossible today.



## 8. Perspectives

### *8.1 Commercial perspective*

The aim of commercial fishermen is to catch species within their quota as efficiently as possible, with minimal bycatch of unwanted species and sizes. An additional factor is to provide catches with the highest possible quality in order to maximize market prices. Although the study demonstrated several advantages of Danish seining over bottom trawling, including a higher catch quality, a simple transformation of the fishery to more seining and less trawling should not be expected. The main reasons are the higher workload of Danish seiners compared to trawlers (Suuronen et al., 2012) and the limited flexibility in targeting different species (**Paper 4**). However, the development of new technologies, like plaice gutting machines, is expected to reduce the workload onboard seiners. In combination with new management strategies, this may contribute to a recovery of the Danish anchor seine fishery in Denmark. The Danish association for gentle coast-fishery (Foreningen for Skånsomt Kystfiskeri founded in 2014) is an example of how this may be realized, as “gentle fishing methods”, like Danish anchor seining, get exclusive rights for providing high quality products caught in a sustainable way. This system may be further developed by labeling their catches, which would increase the prices and the final outcome for the fishermen.

Another strategy to face the issues in the current development of fisheries could be the combinational use of different fishing gears on one vessel. Vessels that can use bottom trawls as well as demersal seines, for instance, could profit from the flexibility of bottom trawling, whilst also using the advantages of seining to catch specific species very efficiently and in high quality. The steady presence of such multi-purpose vessels over the last years (Figure 2) indicated that this approach is applied by the industry to some extent. However, a further increase in the number of such vessels can be expected due to the recent changes in legislation and management. Today, most multi-purpose vessels combine bottom trawling and Scottish seining (see 1.3 Demersal seining in other countries). Although the results of the present study for Danish anchor seining can, to some extent, be translated to Scottish seining, some of the environmental advantages of Danish anchor seining are most likely not present for these vessels, e.g., low levels of sea bed interactions.

## ***8.2 Scientific perspective***

This study increased the scientific knowledge about Danish seining for a wide range of issues, including: the catching method; the codend and full gear selectivity in the seine net; the fishing profile compared to bottom trawls; the seines' interaction with the surrounding environment during the catching operation; and finally, by the development of systems that will allow future studies to collect more detailed information. The study, however, also raises several questions requiring new studies to be conducted in future.

Although the study described in **Paper 1** could describe the global gear geometry of a Danish seine during the catching process, it is important to investigate if the same patterns can be observed when the gear is used in different conditions, e.g., deeper waters. Methods developed within the present study can be used and further developed to conduct such experiment. The data collected within the present study can be used to validate simulation tools that describe the seining process.

Discard survival studies need to be conducted for Danish seines to estimate survival rates of central target species listed within the landing obligation. If handling time on board is kept short, survival of fish discarded by Danish seines is likely higher than for trawls, because fish spend a relatively short time in the seine net (**Paper 1**). If such studies conclude survival rates to be high for certain species, exemptions for those in terms of the landing obligation (Council Regulation (EU) 1380/2013) might be appropriate for Danish seiners.

These survival studies should, however, not only focus on commercial species and not only on the codend catch. The study described in **Paper 3** found that there are interactions between caught animals and the Danish seine, but results could not be translated directly to mortality rates. Therefore, survival studies that combine external damages with internal damages and survival probability of invertebrates are important (Broadhurst, 2006). In case they find low survival rates, there is a need to develop invertebrate release systems, which could be similar to the benthic release panels described by Revill and Jennings (2005) for beam trawls.

In order to test if other factors hid effects of gear or mesh size in the study described in **Paper 4**, future studies should compare catches of seiners and bottom trawlers again, but ensure that additional factors, like area, depth, or season, are the same for both gears.

Finally, future studies need to further investigate the impacts Danish seining has on the sea floor. Underwater video recordings within this study showed that the level of such impacts is likely low, but effects on organisms inhabiting the sea bed could not be assessed. This should be done in future studies, which could be set up as Before-After-Control-Impact (BACI) experiments (e.g., Rosenberg et al., 2003), i.e. two areas are designated to be the study site, where one area is fished by a Danish seine and the other one represents the control site. Comparing individual numbers and biodiversity of both areas, before and after fishing, could then serve as a measure of how Danish seining affects the benthic fauna.

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## **Papers**



## **Paper 1**





# Describing the gear performance of a commercial Danish anchor seine

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## Abstract

Danish anchor seining is an efficient fishing technique and the environmental impacts are considered to be low compared to other fishing methods. The fishing process is, however, poorly described. The current study used sensors and cameras attached to a commercially used Danish seine to describe the gear and rope performance during all stages of the fishing operation. This allowed investigation into how fishermen can optimize this process and to estimate parameters in relation to the gear's impacts on the sea bed. Estimates of wing spread and net height indicated that there is only a limited time period during the fishing process where the net is in an appropriate shape to catch fish efficiently. The majority of fish entered the seine net within the last 25% of the fishing duration and fishermen could adjust the retrieval speed relatively precisely in relation to the entering of the fish. Results about tension forces between seine net and seine ropes indicated forces applied on sea bottom structures to be lower than for demersal otter trawls. In combination with estimates about the area covered by ropes and seine net, the results showed that theoretical estimates about sea bed impacts of Danish seines from previous studies are likely overestimated.

**Keywords: Demersal seining, Sea bed impacts, Seine ropes, Swept area**

## **1. Introduction**

The Danish anchor seine is an active fishing gear, which is commercially used worldwide and recognized as an efficient gear in terms of fuel consumption (Thrane, 2004; Suuronen *et al.*, 2012). Impacts on the marine environment are considered to be low compared to other demersal fishing gears like demersal otter trawls (Suuronen *et al.*, 2012; Eigaard *et al.*, 2015) and catches are categorized as high quality products (Dreyer *et al.*, 2008; Suuronen *et al.*, 2012). In Denmark, the primary targets are flatfish species like plaice (*Pleuronectes platessa*), but seasonally also roundfish species like haddock (*Melanogrammus aeglefinus*) and cod (*Gadus morhua*).

Contrary to most other active fishing techniques, Danish seine fishermen do usually not use any monitoring sensors on their seine net or seine ropes. This is likely due to a generally high age of the vessels and the partly long distance between seine net and fishing vessel, which impedes the transmission of acoustic signals. However, the fishermen have clear expectations about the gear's behavior during the different stages of the seining process, based on experience. These expectations and experiences are the fishermen's basis to optimize the catching efficiency during the different stages of the seining operation. The fishing process of a Danish seine (Figure 1) can be divided into three main phases: setting phase (Figure 1A-C), fish collecting phase (Figure 1D-E) and closing phase (Figure 1F). Briefly summarized, the fish are encircled by long weighted seine ropes which are both connected to the seine net. After encircling the fish, the seine ropes start to be retrieved. This reduces the area between the seine ropes and herds the fish into the middle of the fishing area. Several steps of acceleration in rope retrieval and the final movement of the net herd them into the net eventually. Instead of encircling the whole intended fishing area, the second rope is often laid out as indicated in Figure 1C, resulting in some distance between its end and the anchor, but is then towed back to the anchor. This procedure enlarges the fishing area. Another method of demersal seining is called Scottish seining (Fly-shooting, Fly-dragging). Since Scottish seiners do not use an anchor and the vessel moves forward during the retrieval phase, Scottish seining can be regarded a hybrid between anchor seining and demersal otter trawling (Eigaard *et al.*, 2015).

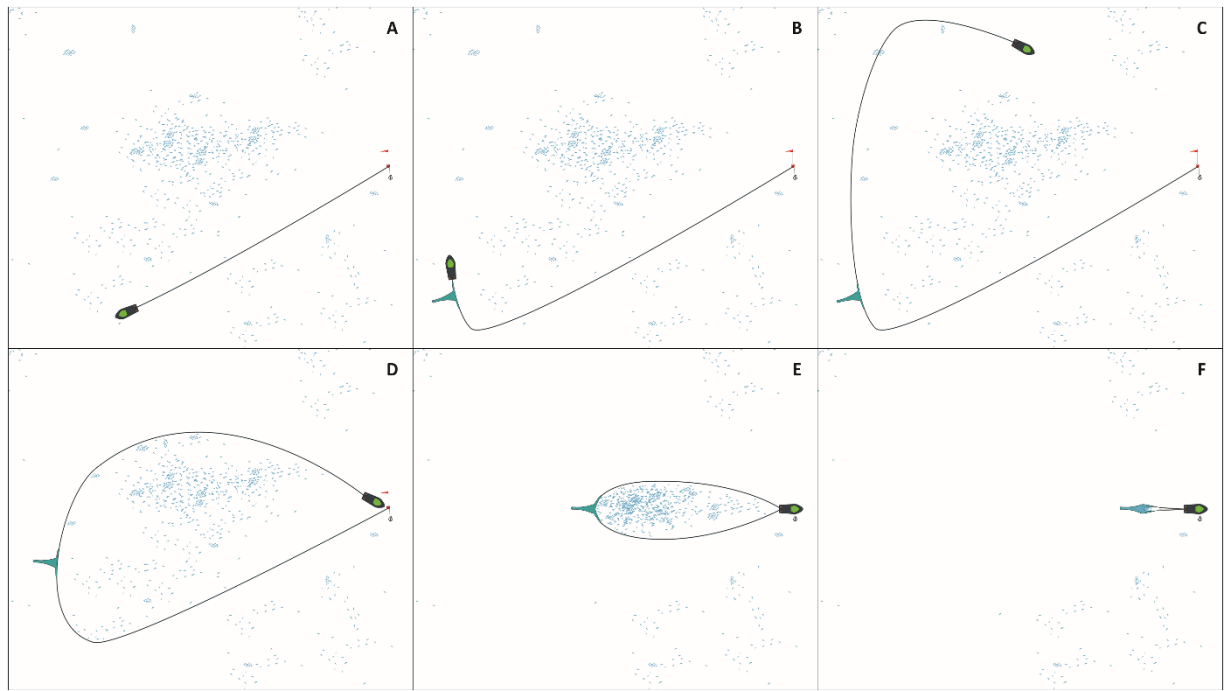


Figure 1. Main phases of the fishing process with a Danish anchor seine: setting phase (A - C), fish collecting phase (D, E), and closing phase (F).

Previous studies have not described how the seine ropes operate during the process, how net geometry changes during the process or when the fish actually enter the gear. These data are, however, necessary to reveal whether catching efficiency could be increased. Although Danish seines and demersal otter trawls show pronounced differences in the way they are used, both gears belong to the same legislative category in the EU legislation. In other regions, Norway for instance, seiners have exclusive rights permitting them to fish in coastal waters that are prohibited for demersal otter trawls (Regulations governing the sea-fishing activities J-125-2016 §15, §53; Norwegian Directorate of Fisheries). It was found that demersal fishing affects the functioning of benthic invertebrate communities by altering their habitats (Reiss *et al.*, 2009), but experimentally validated knowledge about impacts of seines on the sea bed is missing. To be able to evaluate the efficiency and sea bed impacts of Danish seines we need to understand the operation of the Danish seining process and the extent of affected sea bed in detail. Such detailed information is not available today, but relevant for tasks like spatial planning in terms of the Marine Strategy Framework Directive (MSFD; Long, 2011) or other technical regulations.

The present study aims to establish a detailed description of the Danish seine fishing operation by using sets of sensors and cameras. Information about net geometry and fishermen's behavior were combined with information on when fish actually enter the seine net. This allowed to investigate how well fishermen are able to optimize a process that is carried out without using any monitoring devices. Information about the behavior of the seine ropes and the seine net were used to estimate the size of the area affected by seine ropes and seine net during the fishing process. Combined with estimates about tension between the seine net and the seine ropes, those values served for a comparison to forces that demersal otter trawl bridles apply on protruding sea bottom structures. Structures that are potentially affected by horizontally approaching seine ropes or trawl bridles encompass biological components (epifaunal benthic animals or macroalgae) as well as geological components (e.g., stones or sand mounds).

## **2. Materials and Methods**

### *2.1. Study site and gear specifications*

The Danish seining experiments were carried out on board the commercial Danish seiner S15 *Vera Marie* (overall length: 16.13 m, engine power: 140 kW) in waters <10 m in the Kattegat (ICES area IIIaS; Figure 2) in August 2015. The vessels own seine with 360 meshes around the fishing circle (nominal mesh size: 120 mm) and a ground rope (Taifun wire, diameter: 14 mm, weight in air: 0.25 kg m<sup>-1</sup>) of 43.6 m in length was used. The wire was weighted by threading led pieces on it (total led weight: 90 kg). Additionally, the weighted ground rope was wrapped with 16 mm rope made from coconut fibres (0.2 kg m<sup>-1</sup> in air). The codend was made of PET 4 mm double twine material (mesh size: 120.2 ± 2.7 mm, N = 40, measured with an OMEGA gauge (Fonteyne *et al.*, 2007)) with 97 open meshes in circumference and constructed with one selvedge, which included three meshes, following commercial practice. The vessel used two times 15 coils (rope pieces of ~220 m, which add to ~3300 m) of leaded seine ropes ("Icelandic seine rope", diameter: 26 mm, weight in air: 0.56 kg m<sup>-1</sup>) per side, which can be considered to be typical for the fleet. The seine ropes were retrieved towards the anchored vessel using hydraulic rope reels. In all hauls, retrieval

started with relatively low velocities of  $\sim 1.5$  kn ( $\sim 0.8$  ms<sup>-1</sup>) and increased when about half of the rope got retrieved. The speed increased again when both seine ropes were close to each other (when ca. four coils or  $\sim 880$  m of rope were left to retrieve) and again to a maximum of  $\sim 4.6$  kn ( $\sim 2.4$  ms<sup>-1</sup>) when the ropes touched each other (when ca. two coils or  $\sim 440$  m of rope were left to retrieve).

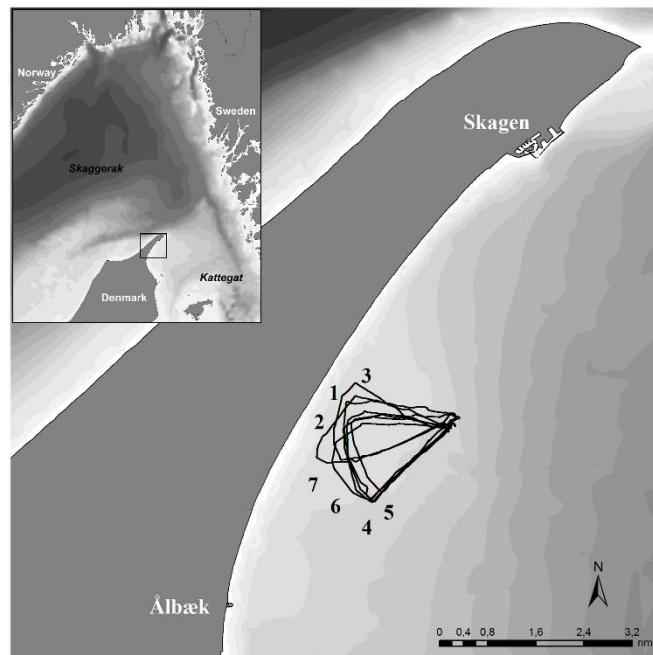


Figure 2. Study area and vessel tracks for the seven hauls conducted for the trials on board the Danish seiner S15 *Vera-Marie* in 2015.

## 2.2. Experimental setup

To track the motion of the vessel and the specific parts of the gear during all stages of the seining process, nine GPS loggers (Canmore G-PORTER GP-102+; accuracy: 2.5 m circular error probable) were used. Each GPS logger provided position (latitude and longitude) every second. For all hauls, one GPS logger was used on board the vessel to track the vessel and eight loggers were attached to the gear at different positions to track movements and geometry of the seine ropes and seine net during the fishing process (Figure 3). The GPS loggers were connected to the gear using a self-developed surface connection system (SCS, Figure 4), which kept the GPS logger above the water surface close to the point of interest of the seine net or the seine rope. The SCS was constructed of a 10-m dog-leash with retraction mechanism (flexi Giant Professional) and a diving buoy with

inner compartment (Mares Apnea; buoyancy: ca. 8 kg) containing a waterproof box (Subgear Mini Dry) with the GPS logger. Two SCSs were attached to both wing ends of the net using a snap hook. Three more SCSs were equally distributed along each seine rope using a shackle to allow rotation of the seine rope without causing twisting with the SCS. To prevent the mechanisms from slipping along the seine rope, two metal rings were attached on the seine rope at each position (Figure 4). The available length of the dog-leash was the reason for our limitations in water depth.

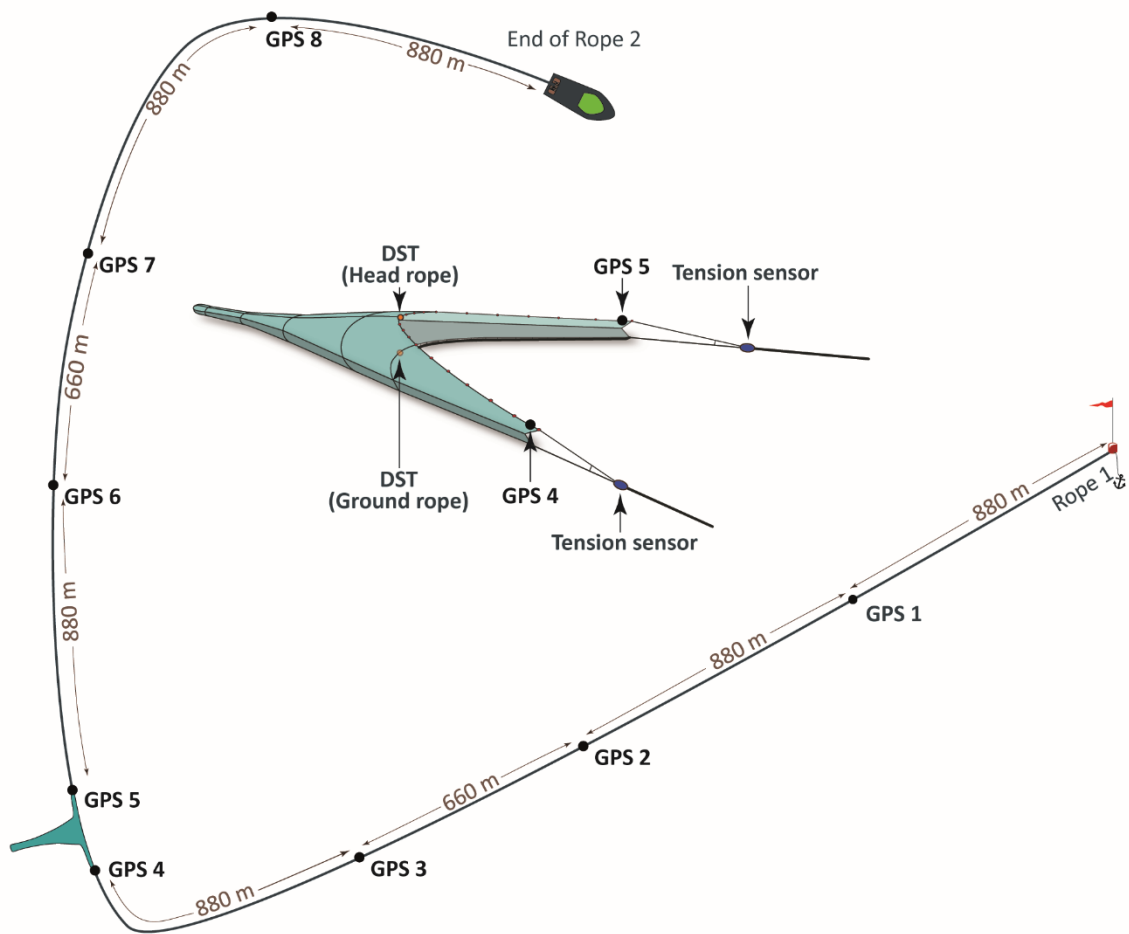


Figure 3. Locations of GPS loggers on ropes and seine net and close-up of seine net with locations of GPS loggers, data storage tags (DST) and tension sensors. Note: One rope is turned around after each haul, thus relative position of GPS 2 is changing after each haul.

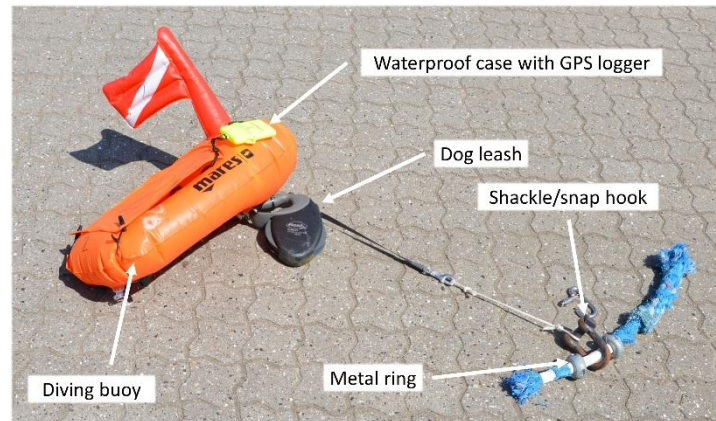


Figure 4. Surface connection system (SCS) including labels for specific parts (for details see text).

Inter-calibrated Data storage tags (DST), measuring salinity, temperature and depth (Star-Oddi CTD; depth accuracy:  $\pm 0.6\%$ ), were mounted at the center of the head rope and the ground rope of the seine net (Figure 3). The loggers recorded depth of both ropes every second allowing for a determination of the vertical opening of the net mouth.

Two tension sensors (NKE instrumentation SF5; range: 5 t, accuracy: 25 kg, resolution: 2.2 kg) were shackled between sweeps and seine net (Figure 3) to record tensile forces on each side of the net during the fishing process every second.

To investigate at which time during the fishing process fish approached the gear and entered the seine net, five time-synchronized underwater video cameras (GoPro, Inc. HERO 3+) were attached to the seine net. Three cameras were attached to the head rope – one in the centre and one in each wing, all three facing forward. Two additional cameras, one facing forward and one facing backward were installed inside the codend. The video recordings provided also information about the seine net's behavior during the fishing process.

The timing of the different stages of the fishing process (start: pay out first rope (Figure 1A), shoot: set seine net (Figure 1B), end rope 2: start towing gear back to the anchor (Figure 1C), anchor: moor to anchor (Figure 1D), end: gear is retrieved (Figure 1F)) was recorded for each haul. All fishing operations were carried out as close to commercial practice as possible, though it was not possible to carry out consecutive hauls in the flower pattern around the anchor point as is it usually

done (Eigaard *et al.*, 2015) due to the requirement of a shallow location. Commercial fishing depths of Danish seiners in the area range from <10 m up to ~100 m.

### 2.3. Data analysis

The combination of time synchronized positions for all GPS loggers provided the basis for visualizing the performance of the seine net and ropes throughout the fishing process. The visualizations used point estimates of the single GPS loggers to show its specific position in the fishing area at a specific time. The simplified geometry of the seine ropes has been estimated using linear interpolation between the point estimates of the loggers. "Polynomial approximation with exponential kernel" smoothing (Bodansky *et al.*, 2002) was used at the point estimates to reduce the sharpness of the edges. In case a GPS logger got submerged and hence was not able to receive GPS-signals, the missing data were estimated as interpolated values using the positions before and after submersion. One visualization is shown exemplarily within the manuscript, but animated versions of the gear performance for all hauls, including information about wing spread (horizontal opening), head rope height (vertical opening), tension forces and observation of fish ("Fish in front of gear", "Fish in codend" and "Codend full of fish") are given in the supplementary material. Wing spread and its changes during the fishing process were estimated by calculating the distance between the GPS loggers at the wing tips. The values, recorded by the depth logger at the head rope, were subtracted from the values of the depth logger at the ground rope in order to calculate the height of the net. Total swept area was estimated as size of the area that had been encircled by the vessel and hourly swept area as total swept area divided by haul duration. Area swept by seine net was estimated as size of the area covered between the two GPS-logger at the wings of the seine net, i.e. GPS 4 and GPS 5).

All analyses were done in R Statistical Software (R Core Team, 2015) and animations of the fishing process were created using ArcGis software.



### 3. Results

#### 3.1. Haul overview and gear performance

Seven valid hauls with a duration ranging from 191 to 268 min were conducted (Table 1). Total catches ranged from 34 to 390 kg and the majority of the catch was composed of plaice and flounder (*Platichthys flesus*). The crew quickly got familiar with attaching and detaching the SCSs, resulting in only short stops during setting and retrieval of the gear. The area swept by the whole gear varied between 4.17 and 5.51 km<sup>2</sup> per haul, but only 0.04 to 0.06 km<sup>2</sup> were swept by the seine net itself and thus, by the ground rope (Table 1). The area that got swept by the whole gear varied between 1.07 and 1.57 km<sup>2</sup> h<sup>-1</sup> (Table 1).

Table 1. Overview of hauls conducted during the experiments. Sea state was recorded following Wileman et al. (1996). Duration refers to the time from start of the fishing process (start laying out the first rope) until when gear was fully retrieved. Furthermore, swept area (size of area encircled by vessel and size of area swept by ground rope), average swept area per hour (total swept area/duration), and additional haul-specific information are given, whereas procedures like removal of algae occur during commercial hauls.

Haul	Date	Sea state	Duration (h:min)	Swept area (km <sup>2</sup> ) total / by seine net	Hourly swept area (km <sup>2</sup> h <sup>-1</sup> )	Remarks
1	13.08.2015	2	4:25	4.72 / 0.06	1.07	-
2	13.08.2015	1	3:17	4.17 / 0.06	1.27	GPS 2 moved 220 m along the rope to next splicing
3	20.08.2015	2	3:14	4.23 / 0.05	1.31	sweep-net-connection broke; left anchor to retrieve
4	21.08.2015	1	4:28	5.51 / NA	1.23	lost GPS 4; several stops to remove algae during haulback
5	21.08.2015	1	3:08	5.00 / NA	1.57	GPS 5 centered; several stops to remove algae during haulback, net teared
6	22.08.2015	2	3:44	4.42 / 0.04	1.18	several stops to remove algae during haulback
7	22.08.2015	2	3:22	4.82 / 0.05	1.43	-

Figure 5 shows an exemplary visualization of haul 5, as during this haul most GPS loggers stayed at the surface for most of the fishing process, resulting in the highest temporal resolution of all seven hauls. It showed that the initial lay-out pattern of the two seine ropes was not symmetrical. It also demonstrated that the seine net did not pass the center of the fished area in a straight line. Colored animations (S1-S7, supplementary material) showed similar patterns for all other hauls.

### Haul 5 - GPS movement

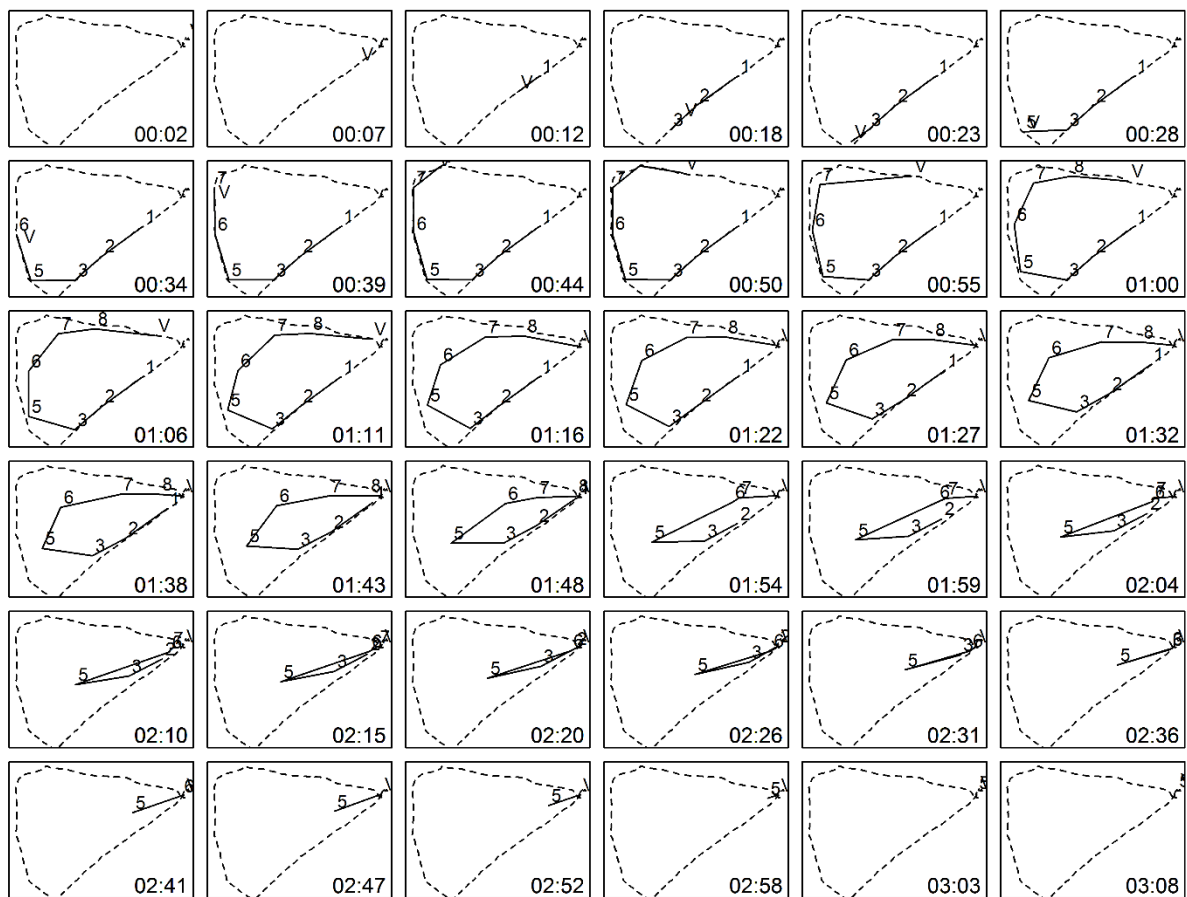


Figure 5. GPS movements and simplified presentation of rope movement from haul 5 over time after begin of fishing process (hours:minutes). Stippled line reflects final vessel path. V is the current position of the vessel and the numbers stand for respective GPS loggers on seine ropes (1,2,3,6,7,8) and seine net (5). Note: GPS 4 could not be used in this haul and GPS 5 was moved to the middle of the head rope.

It was possible to measure the spread between wing tips of the seine net based on GPS-recordings for hauls 1, 2, 3, 6 and 7 (Figure 6 and Figure 7). The maximum spread of around 30 m in the start of the fishing process decreased gradually towards the end of the fishing process where the spread was typically less than 5 m. Except for haul 1, the wing spread always decreased to less than 10 m only within the last quarter of the fishing process. Wing spread curves of all hauls were characterized by abrupt jumps and peaks, which were more pronounced in the later stages of the fishing process.

Measurements of vertical opening could be established for hauls 3 to 7 (Figure 6 and Figure 7). The heights varied between the hauls, but the general pattern was an initial height of ~8 m that decreased down to ~2 m as soon as tension increased (i.e. the seine net starts moving) and increased

back to ~8 m in the last stages of the fishing process when the wing spread decreased. Some jumps in the net height curves could also be seen.

Video recordings of the ground rope (available for hauls 3, 4, 5, 6 and 7) and wing spread estimates were available for hauls 3, 6 and 7. Combining those indicated that the ground rope started to lift slowly from the sea bed when the wing spread became less than ~10 m.

Tension values were collected for all hauls (Figure 6 and Figure 7). Tensile forces were higher on the rope that was set out last, but the values of both sides approached similar values later in the fishing process when the ropes became more symmetrical. Tensile forces at both wings increased towards the end of the fishing process. Particularly high tension values were observed in the final stages of haul 3 until the chain connecting the seine net to one seine rope broke shortly before the end of the process. For all other hauls that provided information about fish entering the seine net, one of the final increases in tension (increase in winch speed) was followed by the point where the majority of fish entered the net. All tension curves were characterized by sudden decreases in tension during the retrieval process.

Net speed was measured for all hauls (Figure 6 and Figure 7). Consistently for all hauls, it increased during the fishing process, but the latter phases were characterized by several abrupt decreases. Those decreases fit the occurrence of decreases in tension and increases in net height.

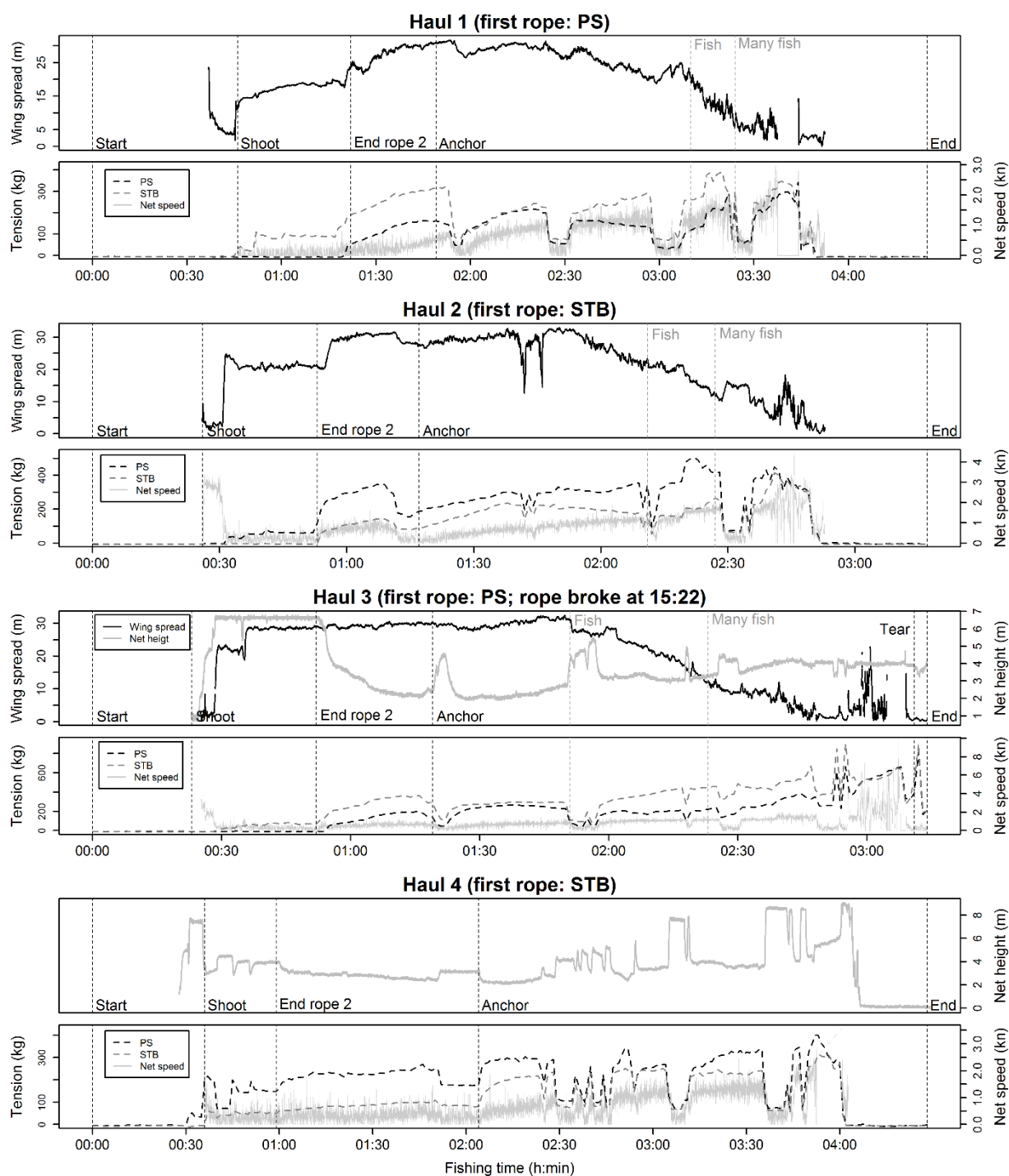


Figure 6. Parameters describing the performance of the Danish seine (wing spread, net height, tension, net speed) for haul 1-4 including time information about fishing process (hours:minutes) and fish observations. Expression in parenthesis indicates which rope was set out first (PS: port side; STB: starboard).

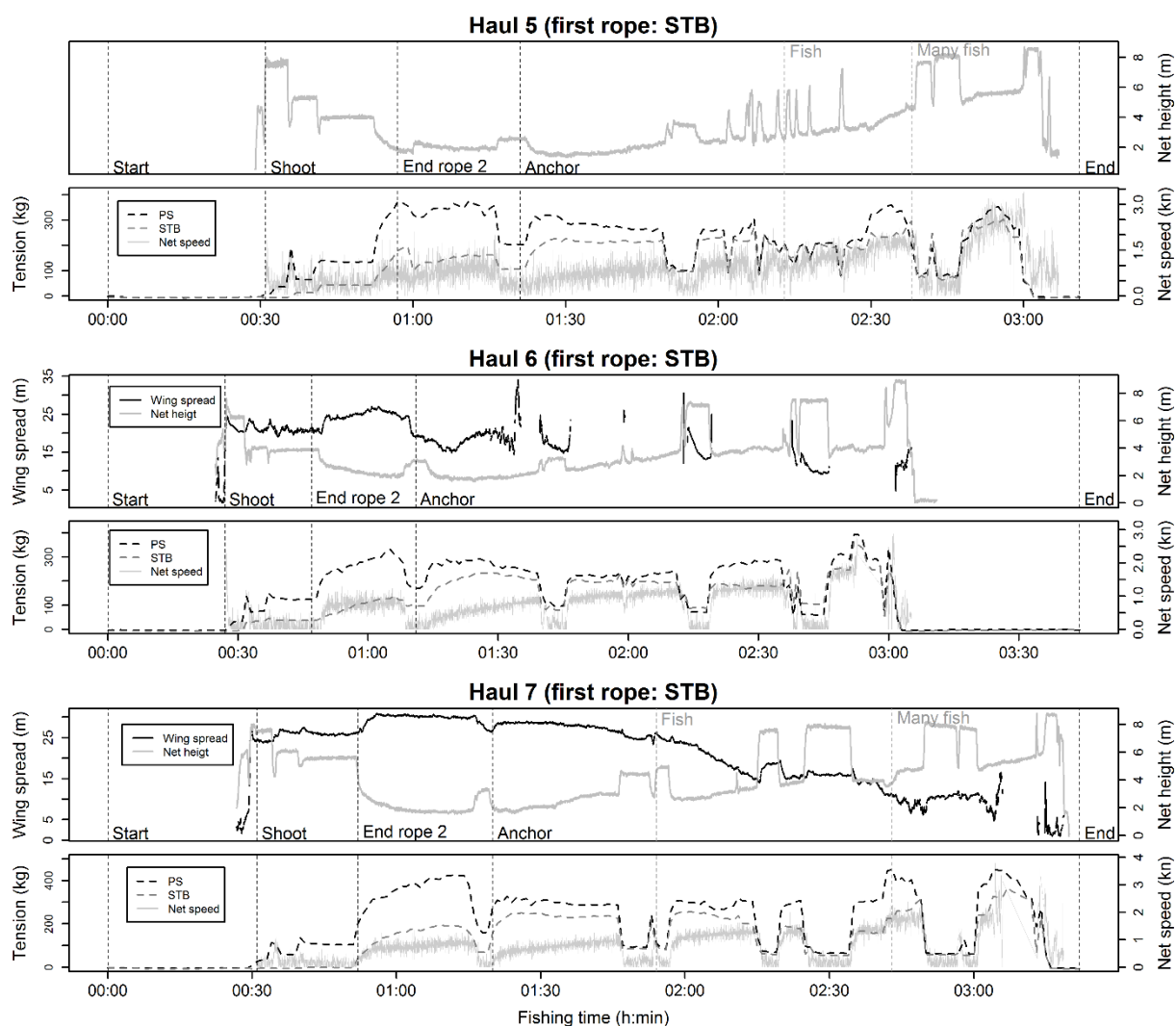


Figure 7. Parameters describing the performance of the Danish Seine (wing spread, net height, tension, net speed) for haul 5-7 including time information about fishing process (hours:minutes) and fish observations. Expression in parenthesis indicates which rope was set out first (PS: port side; STB: starboard).

### 3.2. Observation of fish

The time when fish enter the seine net was observed in hauls 1, 2, 3, 5 and 7 (Figure 6 and Figure 7). Observed species were mainly flatfish species like plaice and flounder, but also roundfish species such as red gurnard (*Chelidonichthys lucernus*) and greater weever (*Trachinus draco*). The moment when the first fishes were observed inside the codend varied considerably. The entry of the catch majority was, however, always within the last quarter of the fishing process. Increasing seine rope retrieval speed to the maximum coincided with the entering of fish. In haul 3, however, most fish entered the net relatively soon before the retrieval speed was increased to its maximum (Figure

6), but this was also the haul where the chain connecting the seine net and the seine rope broke. In haul 1, haul 2 and haul 5, maximum speed was reached shortly before the majority of fish entered the gear (Figure 7). Figure 8 indicates different amounts of fish in the codend.

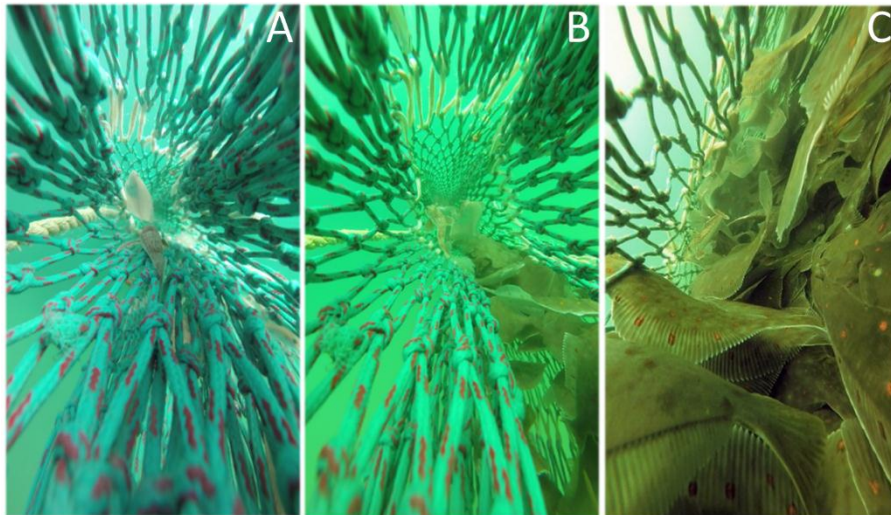


Figure 8. Fish entering the codend. A. First fish enter the codend (early collecting phase; after 2:56 hours, 66% of fishing process). B. Few fish are in the codend (early collecting phase; after 2:59 hours, 67% of fishing process). C. Majority of fish entered the codend (late collecting phase; after 3:23 hours, 76% of fishing process). Note: footage from preliminary haul that could not be used within gear performance analyses (haul duration: 4:26 hours).

#### 4. Discussion

The present study described the overall performance of a Danish anchor seine during all stages of the fishing process providing information about the seine net as well as the seine ropes. The measurements showed consistently that the seine net changed shape considerably during the fishing process and that fish entered the seine net very late. The point estimates of different gear parts during different stages of the fishing process provide further a detailed database that can be used for future studies using software to simulate the performance of Danish seines (or partially Scottish seines) under varying conditions (e.g., different lay-out patterns).

The main reason for the asymmetry observed in the rope lay-out shape and the acting tensile forces was the particular way of laying out the end of rope two some distance to the anchor and towing the remaining distance towards the anchor. This initial asymmetry and the harmonization of both sides later in the process was also found for Scottish seines (Galbraith and Kynoch, 1990).

Contrary to trawls, where the horizontal and vertical opening of the net is relatively stable during the whole fishing process (Priour and de la Prada, 2015; Bertrand *et al.*, 2002), constantly changing values were observed for the Danish seine. This is similar to what has been found for Scottish seines (Galbraith and Kynoch, 1990). The seine net was overspread when set out, resulting in very high wing spread values during the setting process, which can, however, be considered to be an operational characteristic of seine nets. Only when both ropes began to be winched in and both wings were towed equally did the net start to obtain its intended shape and moved towards the vessel. Although this was when the gear became symmetrical and when fish could enter the seine net, only very few fish did so. The underwater observations showed that fish entered the seine late in the fishing process, as also observed for Scottish seines (Herrmann *et al.*, 2016b). For the Danish anchor seine, the majority of fish entered the seine net only in the last quarter of the fishing process, which is a likely explanation for the high quality of catches by Danish seines (Dreyer *et al.*, 2008; Suuronen *et al.*, 2012) because most fish spend only a very limited time inside the netting part of the gear. Furthermore, the net geometry varied considerably during this relatively short period when fish enter the seine net, i.e. the net height increases and the wing spread decreases. However, the geometry of the seine net needs to be correct to catch fish efficiently as it would otherwise be likely that the seine net would not catch all fish that have been herded by the seine ropes. Catching fish ended when the wing spread was <10 m, as the ground rope started to lift from the sea bed and fish could swim underneath. Generally, the majority of fish were observed to enter the codend before the ground rope lifted off the seabed. This showed that fishermen's procedure of setting the gear and increasing winch speed in specific steps worked relatively well although they did not use any equipment to monitor the seine net, the seine ropes or the entering of fish. It also indicates the high level of the fishermen's knowledge about their gear and the process, based primarily on experience. In three hauls, the final increase in speed could have been done just a few minutes later to delay the lifting of the ground rope and thus reduce the chance of herded fish to escape beneath the lifted ground rope, i.e. more fish could have been caught and thus efficiency could have been increased. Since the amount of fish that accumulated in front of the gear during the herding process, the loss of catch can could be rather high if these fish could not be caught.

Patterns of sudden jumps in individual GPS tracks, wing spread curves and net height curves were likely caused by measurement errors (due to submergence of GPS loggers) and by the effects of attaching and detaching the SCSs or removing seaweed and the involved stops of the winches. This hypothesis is supported by the fitting points of decreases in the net speed curve, indicating a slowing down in retrieval. As effects were rather small and occasional stops also happen in commercial practice, e.g., to remove entangled seaweed along the ropes, the general trends of the results can be regarded as reflecting normal commercial conditions. Linear interpolation points were used between the GPS measuring points along the seine ropes which does not reflect the true geometry of the seine rope, but gives a good and simple idea as to how the seine ropes move during the fishing process. Furthermore, the experiments within this study were restricted to water depth <10 m. Although commercial hauls are conducted in many different depths, hauls <10 m are rather uncommon. The results might therefore be different for deeper areas where the gear may perform differently, for instance that the ground rope lifts from the sea bed at a different moment. If this is the case, the fishermen would need to adapt the procedure to keep potential loss of fish as small as possible. An adaption of the used equipment could allow for an investigation of those effects in future trials.

Estimated tension between seine net and seine ropes was less than half of what has been observed as average bridle tension for a bottom trawl of a similar size (329 meshes around the fishing circle; mesh size: 80 mm; Priour and de la Prada, 2015). These lower tension values demonstrated that forces applied by seine ropes on sea bottom structures are not similar to forces by trawl bridles and sweeps as assumed in Eigaard *et al.* (2015), but are likely lower. The ground rope of the gear is due to the additional use of led pieces and wrapped rope constructed in heavier manner than the seine ropes, i.e., potential impacts by the ground gear are likely stronger than by the seine ropes. Relatively low tension values, a generally lighter groundgear and a lower proportion of the total area swept by the seine than assumed (Eigaard *et al.*, 2015: ~10%; current study: ~1%) indicate, however, that sea bed impacts of Danish seines are likely lower than hypothesized by Eigaard *et al.* (2015). This should be considered for future discussions about spatial planning in EU waters and potential bans of fishing gears from marine areas being relevant, e.g., in terms of the MSFD. Future studies should aim at



quantifying these indicated lower impacts of seiners compared to trawlers. If such studies can verify seiners to fish in an environmentally friendly manner, seines could be efficient alternative gears in areas closed for trawling, as it is in Norway (Regulations governing the sea-fishing activities J-125-2016 §15, §53; Norwegian Directorate of Fisheries). Another example are the Netherlands, where the government intends to close several areas in the North Sea for trawl fishing, but still allow gears with lower impacts on the sea bed, e.g., Danish seines (IenM and EZ, 2012).

In summary, the present study allowed to provide a detailed description of the Danish seining process, to show that fishermen can conduct Danish seining in efficient manner and to estimate parameters that give an indication of impacts on the sea bed to be lower than for bottom trawlers and previous estimates of Danish seines. Besides tests in deeper waters and a quantification of these impacts, a consideration in future studies should be the short and intense period in which the total catch enters the seine net. This is of particular interest in waters where trawlers and seiners fish under same technical regulations. Since the catch does not build up continuously over the fishing process, as it is the case for trawls, selective devices like escape windows or selection grids might work differently. Selective devices for seines need to be efficient in the short entry period of relative large catches. Although codend selectivity of Danish seines has been investigated in previous studies (Herrmann *et al.*, 2016a; Noack *et al.*, 2017), future studies should investigate the efficiency of mandatory selective devices in high entrance seine fisheries.

## **Supplementary material**

The following supplementary material is available at ICESJMS online: Supplementary S1 – S7 provide haul animations for the seven hauls conducted within this study. The animations include a time stamp and information about wing spread, net height, tension forces and observation of fish (“Fish in front of gear”, “Fish in codend” and “Codend full of fish”).

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## **Paper 2**





# Codend selectivity in a commercial Danish anchor seine



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## ABSTRACT

Danish seining (or anchor seining) is a fishing technique that is gaining increasing attention because it is considered to be a fuel-efficient fishing method with low environmental impact. However, scientific documentation of the selectivity characteristics of Danish seines is lacking, and the gear generally is grouped with bottom trawls and Scottish seines in fisheries management legislation. In this study, we developed a codend cover to estimate the selectivity of a standard commercial Danish seine codend for four fish species. The data for the dominant species, dab (*Limanda limanda*) and plaice (*Pleuronectes platessa*), was best described by models that combine two or three logistic models, which indicated that more than one selection process was at work. Selectivity of cod (*Gadus morhua*) was best described by a Richard curve and selectivity of red gurnard (*Chelidonichthys lucernus*) by a logistic curve. The estimated selectivity curve of dab indicated, contrary to cod and plaice, low retention of individuals below MLS. Confidence limits for larger length classes of cod and red gurnard were relatively wide. For plaice, the estimated selection factor, which is the length with 50% retention divided by mesh size, was comparable to literature values from trawl studies. The average value for cod was similar for Danish and Scottish seines, but lower for trawls. The results are discussed in the context of fisheries management with focus on the landing obligation of the new Common Fisheries Policy.

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## 1. Introduction

Although a decline in the number of seiners in Denmark is evident (1990: 252; 2000: 118; 2015: 32; EuroStat, 2016), Danish seining is still an important fishing technique. In recent years, interest in Danish seining has increased because it is viewed as a fuel-efficient fishing method (Thrane, 2004) and because its environmental impacts are said to be less than those of other active demersal fishing gears such as beam trawls or bottom trawls (ICES, 2006, 2010; Suuronen et al., 2012; Eigaard et al., 2015). The main target species of Danish seiners in Skagerrak and the North Sea are flatfish, primarily plaice (*Pleuronectes platessa*), which has been within safe biological limits for the last three years (ICES, 2015). Nevertheless, there is a general lack of scientific documentation of the selectivity of Danish seines. The sparse existing data (e.g., ICES, 2010; Suuronen et al., 2012) are often based on assumptions or older studies, where other regulations existed, different gears or vessels were used or where data were not analysed following the standards described in Wileman et al. (1996).

A new Common Fisheries Policy that includes a landing obligation (discard ban) system was introduced in most European Union (EU) waters, including Skagerrak and the North Sea, by 1 January 2016 (EEC, 2011, 2012; Condie et al., 2014a,b; Eliassen, 2014; Uhlmann et al., 2014; Sardà et al., 2015). The specific challenge for the industry, and the major difference from the earlier landing quota system is that the catch of all sizes of listed species is counted against the quota. A minimum conservation reference size (MCRS, generally equal to current minimum landing size, MLS) will be introduced for several commercial species and individuals below this size are prohibited from being sold for direct human consumption. Consequently, information about the selective properties of fishing gears is of great importance for the economy and fisheries management as selectivity parameters like L50 (length at which 50% of the fish are retained) and SR (selection range; L75–L25) give an indication of which sizes of fish can be expected by the fishery. This information is important to estimate the probability that the fisheries will adhere the objectives of the landing obligation. Furthermore, if the expectations of the landing obligation are too high (e.g. due to high bycatches of fish below MCRS), the data may allow for recommendations to be made on how to adjust the fisheries to the new system.

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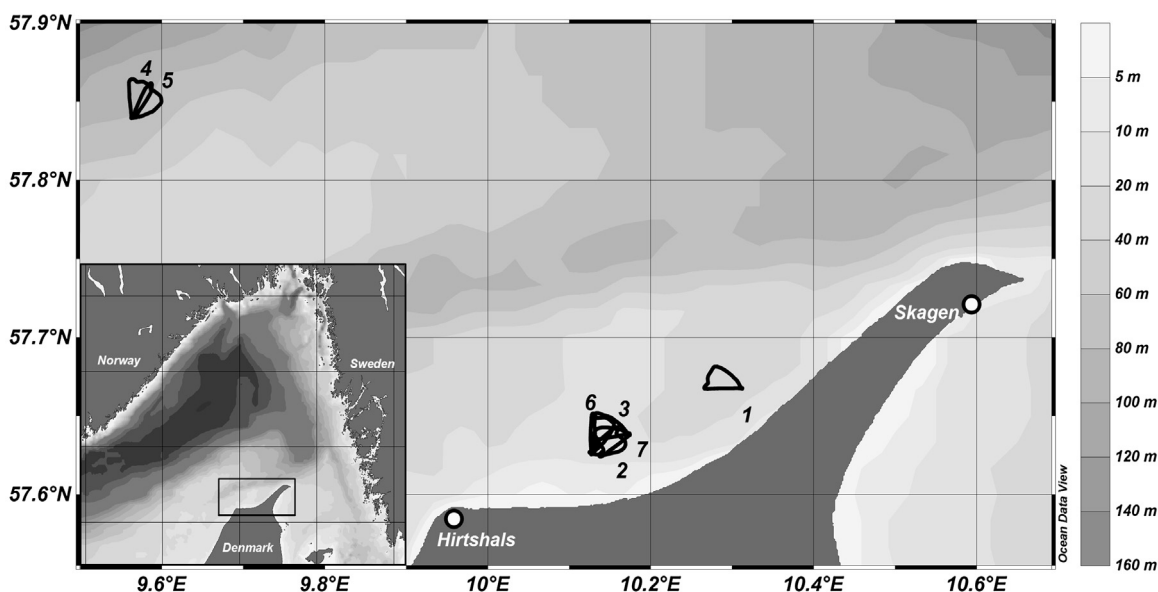


Fig. 1. Area and vessel tracks for the seven hauls conducted for the codend selectivity trials aboard the HG 35 *Vendelbo* in 2014.

By EU law, Danish seines belong to the same legislative category of fishing gears as Scottish seines and bottom trawls. All three gears follow the same technical regulations such as mesh size and selective devices. Several older studies regarding selectivity of Scottish seines exist (Reeves et al., 1992; Isaksen and Lokkeborg, 1993), but the overall state of knowledge is low. A recent theoretical study by Herrmann et al. (2015) estimated the selectivity of Scottish seines on the basis of one of those earlier studies using suitable statistical methods. Nevertheless, they concluded that further studies have to be conducted using currently used demersal seines. The understanding of selectivity in bottom trawls is much greater as the majority of selectivity studies for gears from this legislative category focused on trawls (e.g., Reeves et al., 1992; Graham et al., 2004; Frandsen et al., 2010b; Madsen et al., 2012).

Although the netting materials and codend constructions used in Danish seines, Scottish seines, and bottom trawls are similar, the gears have pronounced differences in construction and in the way they are operated. Bottom trawls use trawl doors to spread the net (von Brandt, 2005), and the towing speed is relatively constant throughout the fishing process. Seiners do not use any doors or other spreading devices, and the speed at which the net is dragged is slower than that in trawling, but it continuously increases during the fishing process. Scottish seiners move forward during the retrieval process, whereas Danish seiners do not as they are anchored (von Brandt, 2005). With such pronounced differences in towing speed and net geometry during the fishing process, it is likely that the selection processes differ among the three types of gears.

Due to the lack of consistent forward motion in Danish seines, it is important to develop a cover based on the principles of the conventional codend cover (Wileman et al., 1996) to study the selectivity of this type of gear. Such a device must cope with the different stages of the fishing process and always keep the cover a sufficient distance away from the codend to avoid a potential masking effect that can occur when the cover comes in contact with the meshes of the codend (Madsen and Holst, 2002).

The main objective of this study was to estimate the selectivity parameters for species caught with Danish seines using the codend design currently used in the commercial fishery. These selectivity parameters were compared to those of bottom trawls and Scottish seines, and the results should prove useful in terms of technical

regulations and management policies. The data will also be used to evaluate the gear in terms of the landing obligation and to estimate the potential consequences for the Danish seine and bottom trawl sector now, and in the future, should other species be added to the landing obligation list.

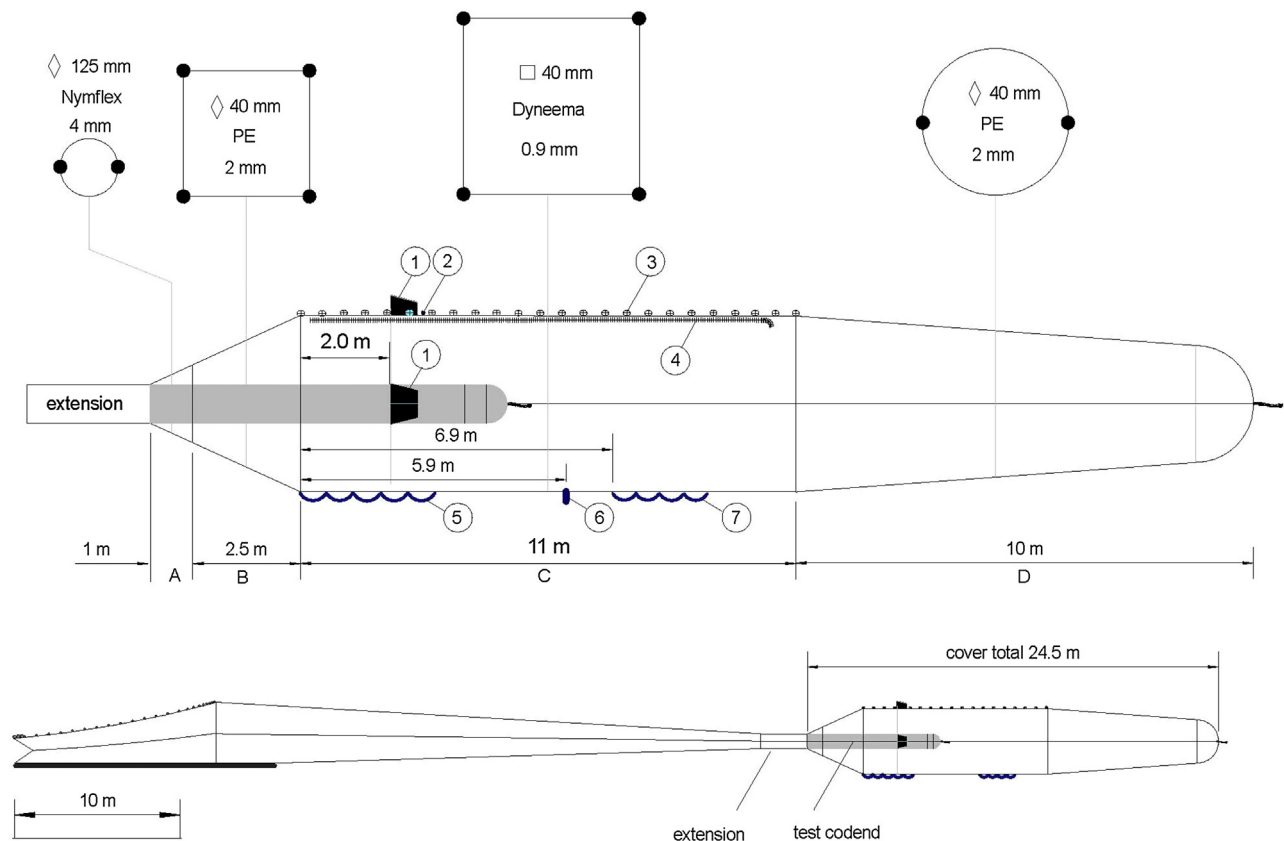
## 2. Materials and methods

### 2.1. Study site and experimental setup

The experiments were carried out aboard the commercial Danish seiner HG 35 *Vendelbo* (length overall: 15.47 m, engine power: 91 kW) off the coast of Denmark in Skagerrak (ICES area IIIa; Fig. 1) in August and September 2014. The fishing took place in sandy shallow areas close to the coast (~13 m deep, Hauls 1, 2, 3, 6, 7) that are known to be good grounds for flatfish such as plaice and in deeper grounds (~68 m deep, Hauls 4 and 5) that are known to be good for roundfish such as haddock (*Melanogrammus aeglefinus*).

The vessel's commercial gear was used, which was representative for the Danish seining fleet that operates in Skagerrak and the North Sea. The seine had 380 meshes (nominal mesh size: 120 mm) around the fishing circle, and it consisted of a wing section with a weighted 43.6 m long ground rope, a belly section, and an extension section. The 7 m long non-tapered codend was made of Nymflex 4 mm double twine polyethylene (PE) netting (mesh size:  $124.4 \pm 3.0$  mm,  $N=200$ , measured with an OMEGA gauge (Fonteyne et al., 2007)) with 97 open meshes around the circumference. The codend was constructed with one selvedge that included three meshes, following commercial practice. Although scientific selectivity studies are normally carried out with newly produced codends without additional devices (e.g., round straps, protecting bags, or flappers) that could affect selectivity, the codend in this study was equipped with two round straps (Fig. 2; Herrmann et al., 2006). These two round straps were 1.9 m in circumference and mounted 0.5 m ahead of the codline and 2.9 m in circumference and mounted 1.0 m ahead of the codline. Round straps are widely used by commercial vessels to limit a codend's circumference just in front of the codline to facilitate fast and more controlled emptying of the codend aboard the vessel, which is thought to improve safety for fishermen handling the gear. However, small variations of the specific mounting of these round straps may occur between





**Fig. 2.** Schematic drawing of the codend cover and its attachment to the seine including information about modifications to account for different stages of the fishing process (kites, floats, lead ropes, PE bar). Information about netting and number of panels/selvages in the specific parts is also included (cross sections in top of drawing). A and B are necessary parts to attach the cover to the seine net. C represents part of the cover around the area of the codend where the main selection is expected to take place and D serves for storing the fish in the cover. 1: Kites. 2: 1.9 m PE bar (transversal). 3: Floats. 4: Zipper. 5: 3 m long lead rope. 6: 1.7 m long lead rope (transversal). 7: 2.1 m long lead rope.

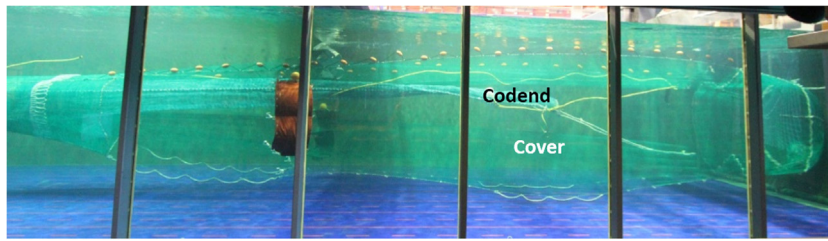
vessels. Legal regulations regarding round straps are stated in EU regulation 3440/84. The seine warps used in the current trials were ~2860 m long (13 coils), each with a diameter of 21 mm.

The covered codend method (Wileman et al., 1996) was applied to catch individuals escaping from the codend. The actual cover was 21 m long and consisted of two main parts (part C and D, Fig. 2), but two additional pieces of netting (part A and B, Fig. 2) were necessary to attach the cover appropriately to the extension part of the seine. The 11 m long part C covered the codend and was made of 0.9 mm thin knotless Dyneema (ultra-high molecular weight PE) twine netting in square mesh orientation (mesh size:  $46.2 \pm 3.0$  mm) to ensure good water flow through the meshes and a low visibility of the netting in order to not affect the escape behaviour of the fish. Furthermore, this configuration allowed the meshes to stay in a fixed position and thus maintain a sufficient opening and distance between codend and cover in order to minimize the risk of masking the codend (Madsen et al., 2001). This part consisted of four panels and had 620 mesh bars in circumference (155 per panel). The 10 m long aft part D was made of 2 mm knotless PE netting (mesh size:  $40.8 \pm 0.7$  mm) in diamond orientation. It consisted of two panels and the number of meshes per panel decreased from 175 in the front to 145 meshes per panel in the end. Three kites, consisting of two PVC-coated trapezoidal canvas parts (ca.  $0.5 \text{ m}^2$  per trapezoid) as described by Madsen et al. (2001) were attached to the cover to ensure that it remained open during faster hauling speeds (Figs. 2 and 3). One kite was attached to each of the starboard panel, the portside panel and the top panel (Figs. 2 and 3). Because Danish seines are dragged at a slower speed than trawls, especially in the beginning of the fishing process, several modifications were made

to the cover design described in Madsen et al. (2001). These were made to ensure that the cover did not mask the codend (Madsen and Holst, 2002) at the low dragging speed. Twenty-four egg-shaped floats (buoyancy: 0.2 kg) were attached along each upper selvedge of the front part, and lead ropes (1 kg/m) were attached to the lower panel (Figs. 2 and 3). Additionally, a 1.9 m long PE bar was fixed transversally across the upper panel at the point where the kites have been attached (Figs. 2 and 3). This ensured the cover to spread horizontally and thus allowed sufficient horizontal space between the codend and cover when the gear was not moving or was moving very slowly. This minimized the risk of masking. Finally, a ca. 10 m long zipper was inserted in the top panel of part C to allow handling the codend catch first in order to prevent escapes of fish from the codend into the cover at the surface (Fig. 2). Adjustment and inspection of the cover were conducted in a flume tank (SINTEF, Hirtshals, Denmark) prior to the experiments, with participation of scientists, fishermen, and the net maker who created the cover. Velocities from 0 to 1.8 kn (0.9 m/s), equivalent to the speed of the seine when the majority of fish enter the codend (unpublished data, Thomas Noack, DTU Aqua Hirtshals, Denmark), were tested. As the length of the cover exceeded the flume tank's dimensions, the last part of the cover was bundled for the tests. By doing so, it was still possible to judge and adjust the modifications around the codend (lead ropes, floats, kites, PE bar) in an appropriate way.

## 2.2. Data collection and sampling strategy

For each haul, fishing time, depth at the position where the net was deployed, depth at anchor and the sea state were recorded



**Fig. 3.** Preliminary assessment of the cover with wrapped rear part in flume tank. For clarification of parts of cover and items attached to it see Fig. 2 and section 2.1.

following the protocol of [Wileman et al. \(1996\)](#). A GPS-logger (Canmore G-PORTER GP-102+) tracked the vessel's movement over the entire fishing process for each haul.

When the catch came aboard the vessel, the codend was emptied first to avoid any fish escaping from the codend into the cover. In order to do so, the cover was tightened up to a level that allowed for a proper opening of the zipper without risking any fish to swim or fall out. As soon as this level was reached, the codend was pulled out of the cover. With the exception of the first haul in which the whole catch was sorted prior to subsampling, subsamples were taken from the non-sorted catch due to large amounts of fish (as outlined by [Gerritsen and McGrath \(2007\)](#)). After sorting and identifying species, fish were measured to the nearest cm. Individual weights were estimated using length-weight relationships ([Shanks, 1981](#); [Coull et al., 1989](#); [Marčeta, 2013](#)).

During the second haul, two underwater video cameras (GoPro, Inc. HERO 3+) were mounted between the cover and codend (pointing downstream and upstream) to document the performance of the cover and the behaviour of the fish in the gear during the fishing process.

### 2.3. Data analysis

Selectivity modelling was conducted to estimate species-specific selectivity curves and selectivity parameters (e.g.,  $L_{50}$  and  $SR$ ) using the computer software SELNET ([Herrmann et al., 2012](#)). Hauls with < 10 measured individuals were excluded from further analyses following [Krag et al. \(2014\)](#). The modelling approach followed the procedure described by [Sistiaga et al. \(2010\)](#), [Eigaard et al. \(2011\)](#), [Herrmann et al. \(2012\)](#), and [Madsen et al. \(2012\)](#). In addition to the logistic model (Eq. (1)), six other models (Eqs. (2)–(7)), including the three other classical size selection models “probit” (Eq. (2)), “Gompertz” (Eq. (3)) and “Richard” (generalised logistic model with additional asymmetry parameter  $1/\delta$ , Eq. (4)) were tested within this study. For detailed descriptions of those see [Wileman et al. \(1996\)](#). Additionally, three more complex models that combined two or three logistic models were considered as candidates. Those were the double logistic model “LogitS2” (Eq. (5); [Lipovetsky, 2010](#)), the dual selection logistic model “Dual.selection” (Eq. (6); [Sistiaga et al., 2010](#)) and the triple logistic model “LogitS3” (Eq. (7); [Frandsen et al., 2010a](#)). All models accounted for overdispersion due to haul-pooling. The retention probability  $r$  of a fish of length  $l$  can be expressed by  $r(l, \nu)$  with  $\nu$  describing a vector that contains parameters needed by the model.

$$r(l, \nu) =$$

$$\text{Logit}(l, L_{50}, SR) \quad (1)$$

$$\text{Probit}(l, L_{50}, SR) \quad (2)$$

$$\text{Gompertz}(l, L_{50}, SR) \quad (3)$$

$$\text{Richard}(l, L_{50}, SR, 1/\delta) \quad (4)$$

$$\begin{aligned} \text{LogitS2} &= c_1 \times \text{Logit}(l, L_{501}, SR_1) + (1.0 - c_1) \\ &\times \text{Logit}(l, L_{502}, SR_2) \end{aligned} \quad (5)$$

$$\begin{aligned} \text{Dual.selection} &= (1.0 - c_1) \times \text{Logit}(l, L_{502}, SR_2) + c_1 \\ &\times \text{Logit}(l, L_{501}, SR_1) \times \text{Logit}(l, L_{502}, SR_2) \end{aligned} \quad (6)$$

$$\begin{aligned} \text{LogitS3} &= c_1 \times \text{Logit}(l, L_{501}, SR_1) + c_2 \times \text{Logit}(l, L_{502}, SR_2) \\ &+ (1.0 - c_1 - c_2) \times \text{Logit}(l, L_{503}, SR_3) \end{aligned} \quad (7)$$

Models that combine two logistic models have been used in previous studies on trawls separating the selectivity process in a towing phase and haul-back phase ([Herrmann et al., 2013a](#)). They have also been used in studies on trawls with sorting grids ([Kvamme and Isaksen, 2004](#); [Sistiaga et al., 2010](#); [Herrmann et al., 2013b](#)) where the individual fish can escape either through the grid or through the codend meshes. For the double logistic model LogitS2 (Eq. (5)) and dual selection model Dual.selection (Eq. (6)), the selection process is assumed to consist of two processes. The double logistic model (Eq. (5)) combines two logistic models, one for the first process and one for the second process. The contact ratio parameter  $c_1$  indicates hereby the probability for an individual to have its selectivity determined by the first process, i.e. the chance of each individual to get in contact with the selective area within the first process ([Herrmann et al., 2013a](#)). Consequently, the probability to have its selectivity determined by the second process is  $1.0 - c_1$ .  $L_{501}$  and  $SR_1$  or  $L_{502}$  and  $SR_2$  describe the selectivity of the according “sub-process”. The dual selection model (Eq. (6)) is similar to the double logistic model, but it is a sequential function. This means that the proportion of individuals that try to escape in the second process is assumed to consist of those that did not attempt to escape in the first process and additionally those that attempted to, but were retained. The triple logistic model LogitS3 (Eq. (7)) follows the same principles as the LogitS2, but includes a third stage of selection, i.e. it is the sum of three logit models in which the weights of the contributions add up to 1.0 ([Frandsen et al., 2010a](#)). Additional parameters required by this model to describe selectivity are  $L_{503}$  and  $SR_3$  explaining the selection in the third “sub-process” and  $c_2$  indicating the probability of an individual to have its selectivity determined by the second process. Consequently, the chance of an individual to have its selectivity determined by the third process is  $1.0 - c_1 - c_2$ .

Selecting the final model for each species followed the procedure of inspecting goodness of fit as described by [Wileman et al. \(1996\)](#) and by comparing individual Akaike information criterion (AIC) values ([Akaike, 1974](#)). If the fit statistics indicated a lack of model fit, i.e. p-value close to zero, deviance  $\gg$  degree of free-

**Table 1**

Overview of hauls conducted for the codend selectivity trials aboard the HG 35 *Vendelbo* in 2014, including information about time, haul conditions, and total catches. Duration describes time from setting anchor until gear was retrieved aboard the vessel. Depth is for the position where the anchor was set and where the seine was deployed. Sea states as described by [Wileman et al. \(1996\)](#).

Haul	Date	Duration (min)	Covered area (km <sup>2</sup> )	Depth (m)		Sea state	Total Catch (kg)	
				Anchor	Seine		Codend	Cover
1	29.08.2014	136	2.69	25.6	18.3	1	1503	8415
2	01.09.2014	136	2.85	12.8	9.1	2	198	1328
3	01.09.2014	137	3.04	12.8	12.8	2	207	1275
4	02.09.2014	122	2.83	65.8	82.3	2	512	1174
5	02.09.2014	121	2.58	65.8	56.7	2	470	1068
6	03.09.2014	140	2.93	7.3	11.0	2	65	327
7	03.09.2014	135	2.82	7.3	12.8	1	69	1023

**Table 2**

Analysed catch data including information about length range, number of measured individuals, and sampling ratio. Current MLS (minimum landing size; if available) is given in parentheses. \* indicates species that will have a minimum reference conservation size in the future. NA indicates that there is no MLS present for this species.

Species	Length range (cm)	Codend		Cover	
		No. measured	Sampling ratio	No. measured	Sampling ratio
Cod (30 cm)*	10–78	620	1	1070	0.272
Dab (25 cm)	9–36	1053	1	4903	0.063
Plaice (27 cm)*	9–51	2937	0.353	3404	0.109
Red gurnard (NA)	9–41	427	1	458	0.287

dom (DOF) or low  $R^2$ -value (ratio of variance explained by model and observed variance), residuals were inspected for any structural deviation to determine if structural problems with the model or overdispersion of the data ([McCullagh and Nelder, 1989](#)) were causing such results. Uncertainties were estimated by calculating Efron 95% confidence intervals (CIs; [Efron, 1982](#)) for the final selectivity curves and selectivity parameters.

Selectivity estimates were compared to values from previous studies of Scottish seines and trawls in the Northeast Atlantic mixed fishery using the estimated selection factor ( $SF = L50/\text{mesh size}$ ). All studies used codends similar to the one used in the present study (mesh orientation: diamond meshes; mesh size: 90–150 mm; twine: 4–6 mm double twine; no grids or release panels), all studies analysed data following guidelines set by [Wileman et al. \(1996\)](#) and all studies were published in peer-reviewed scientific journals. To account for differences in mesh size measurements due to the use of different tools (ICES gauge, EU wedge, OMEGA gauge), values were standardized to EU wedge values ( $\text{wedge} = 0.974 \cdot \text{OMEGA} + 2.96$ , derived from [Ferro and Xu \(1996\)](#) and [Frandsen et al. \(2009\)](#);  $\text{wedge} = 1.01 \cdot \text{ICES} + 2.96$  ([Ferro and Xu, 1996](#))).

All analyses other than the modelling approach were performed using R Statistical Software ([R Core Team, 2015](#)).

### 3. Results

#### 3.1. Haul and catch overview

Seven valid hauls were conducted ([Table 1](#)), which took between 121 and 140 min from setting out the anchor until the gear was retrieved. Each haul covered an area between 2.58 and 3.04 km<sup>2</sup>, and depths varied between 7 and 82 m. Catches ranged from 65 to 1503 kg in the codend and from 327 to 8415 kg in the cover. Thirty-one different fish species were caught in this study and the majority of the catch was composed of dab (*Limanda limanda*) and plaice. Other species investigated within this study were cod (*Gadus morhua*) and red gurnard (*Chelidonichthys lucernus*).

The inspection of the cover in the flume tank and the underwater recordings from haul 2 indicated that the cover did not mask the codend at any speed within the tests or at any stage of the fishing process in the observed haul. Fish escaping from the codend were not observed to swim back into the codend, although they could

easily do so because of the slow towing speed. The observations indicated that the majority of the catch entered the gear relatively late in the catching process. All fish seemed to be in good condition during the whole fishing process and during the handling of the catch on-board.

#### 3.2. Selectivity estimations and length distributions

Selectivity curves and parameters were estimated for dab, cod, plaice and red gurnard ([Tables 2, 3](#)). Low numbers of individuals, in combination with relatively high proportions of small fish, resulted in high levels of uncertainty in the analyses. This prohibited an appropriate estimation of selectivity parameters for the other species. A rather high proportion of small fish was also evident for all species where selectivity analyses were possible as the number of individuals in the codend represented only a small part of the total catch ([Fig. 4](#)), indicating high numbers of fish escaping into the cover.

A Richard curve with relatively smooth rise described the selectivity of cod best (lowest AIC value, [Fig. 4](#)). The model fit was acceptable ( $p$ -value = 0.81, deviance  $\approx$  DOF,  $R^2 = 0.93$ ; [Table 3](#)). Confidence intervals became relatively wide for a range of length classes where the number of observed individuals was low up to length classes with a retention probability of 1.0. The estimated average L50 of 41.6 cm was higher than the current MLS and had, like the estimated SR (12.6 cm), relatively wide confidence limits ([Table 3, Fig. 4](#)).

The selectivity of dab was best described by a triple logistic model ([Fig. 4](#)) and the model fit was good ( $p$ -value = 0.35, deviance  $\approx$  DOF,  $R^2 = 1.00$ ; [Table 3](#)). Most observed individuals were found in length classes below the selective area of the gear, but almost all of them were larger than the current MLS of 25 cm ([Fig. 4](#)). The selectivity curve itself was steep with narrow confidence limits. L50 was estimated to be larger than the current MLS of 25 cm (31.2 on average, [Table 3](#)) and SR was found to be narrow (0.8 cm, [Table 3](#)).

A double logistic model best described the selectivity of plaice. Model fit parameters were good ( $p$ -value: 0.84, deviance  $\approx$  DOF,  $R^2 = 1.00$ ; [Table 3](#)). Most individuals belonged to length classes of the lower range of where selectivity took place, but confidence limits of the steep curve were narrow for all length classes. The current

**Table 3**  
Summary of model parameters (L50 as length with 50% retention, SR as selection range) with 95% confidence limits, name of model used, and values describing goodness of fit (DOF = degree of freedom). See sections 2.3 and 3.2 for explanations of selectivity parameters and model fit values.

Parameters	Cod	Dab	Plaice	Red gurnard
L50	41.6 (27.2–46.4)	31.2 (29.6–31.6)	29.1 (28.7–30.1)	31.0 (28.6–38.7)
SR	12.6 (4.8–16.0)	0.8 (0.1–2.7)	2.2 (1.7–3.6)	11.5 (7.9–26.6)
1/δ	0.5 (0.1–1.3)	–	–	–
L50 <sub>1</sub>	–	31.3 (30.4–148.6)	29.4 (29.1–30.5)	–
SR <sub>1</sub>	–	0.5 (0.1–59.5)	1.4 (1.0–10.4)	–
L50 <sub>2</sub>	–	29.8 (16.1–31.3)	25.5 (20.0–29.7)	–
SR <sub>2</sub>	–	2.2 (0.1–20.3)	6.5 (1.6–11.0)	–
L50 <sub>3</sub>	–	28.0 (0.1–30.0)	–	–
SR <sub>3</sub>	–	15.1 (0.1–00.0)	–	–
Contact ratio 1	–	0.7 (0–1.0)	0.7 (0.1–0.9)	–
Contact ratio 2	–	0.2 (0–1.0)	–	–
Model	Richard	LogitS3	LogitS2	Logit
P-value	0.8101	0.3499	0.8423	0.0000
Deviance	45.70	21.92	26.69	71.67
DOF	55	20	35	24
R <sup>2</sup> -value	0.93	1.00	1.00	0.33

MLS of 27 cm fell within the selective area and laid within the confidence limits for the estimated L50 (average = 29.1 cm, Table 3). SR was estimated to be 2.2 cm (Table 3).

The selectivity of red gurnard as the only species without MLS (Table 2) could be best described by a logistic model. Since the low p-value (0.00) indicated a potential lack of model fit (Table 3), the residuals were investigated. As structures were not detected, it was assumed that overdispersion was at fault and the model could be applied with confidence. The curve had a smooth rise, but was – especially for length classes with retention probabilities above 0.5 – characterized by few observations and wide confidence limits. The estimated L50 and SR values were 31.0 cm and 11.5 cm, respectively (Table 3).

#### 4. Discussion

The goal of this study was to investigate codend selectivity characteristics for several species of fish in a commercial Danish seine as it is currently used in the Danish fishery off the coast of Denmark. An important part of the experimental work was the development of a covered codend methodology that functions at varying towing speeds, but particularly at low or no speed. Both flume tank observations and underwater observations indicated that the current approach of combining floats, weights, a distance bar, and kites with a cover made of four panels functioned very well. Thus, this methodology could be applicable in other, similar fisheries where towing speeds are low and variable.

The commercial Danish seine used in this study usually includes two rear round straps. Round straps could reduce the mesh opening in a codend and hence the size selectivity by reducing L50, as demonstrated by Herrmann et al. (2006) in a simulation study of haddock in trawls. For flatfish, where the morphology of the fish fits a low mesh opening angle, theoretically, the reverse effect could be expected. Because of this, the comparison among trawls, Scottish seines, and Danish seines could be influenced by the round straps, as previous studies used codends without any additional devices. However, effects of other selectivity-influencing factors, such as catch rates, are considered to be stronger than the effects of round straps (Herrmann et al., 2006).

It was possible to estimate selectivity curves for 4 of the 31 caught fish species. The codend mesh size was relatively large, which resulted in low retention for most species. Furthermore, catches of many non-target species were low. For red gurnard, a mismatch between the caught population structure and the selective area of the mesh size was observed, i.e. most observed fish were between 10 cm and 30 cm, but our model found that full retention was not obtained below 40 cm. For cod, which can grow bigger, the

**Table 4**

Comparison of estimated selection factors (SFs) between this study and previous selectivity studies of Scottish seines and trawls. Data values are mean and range.

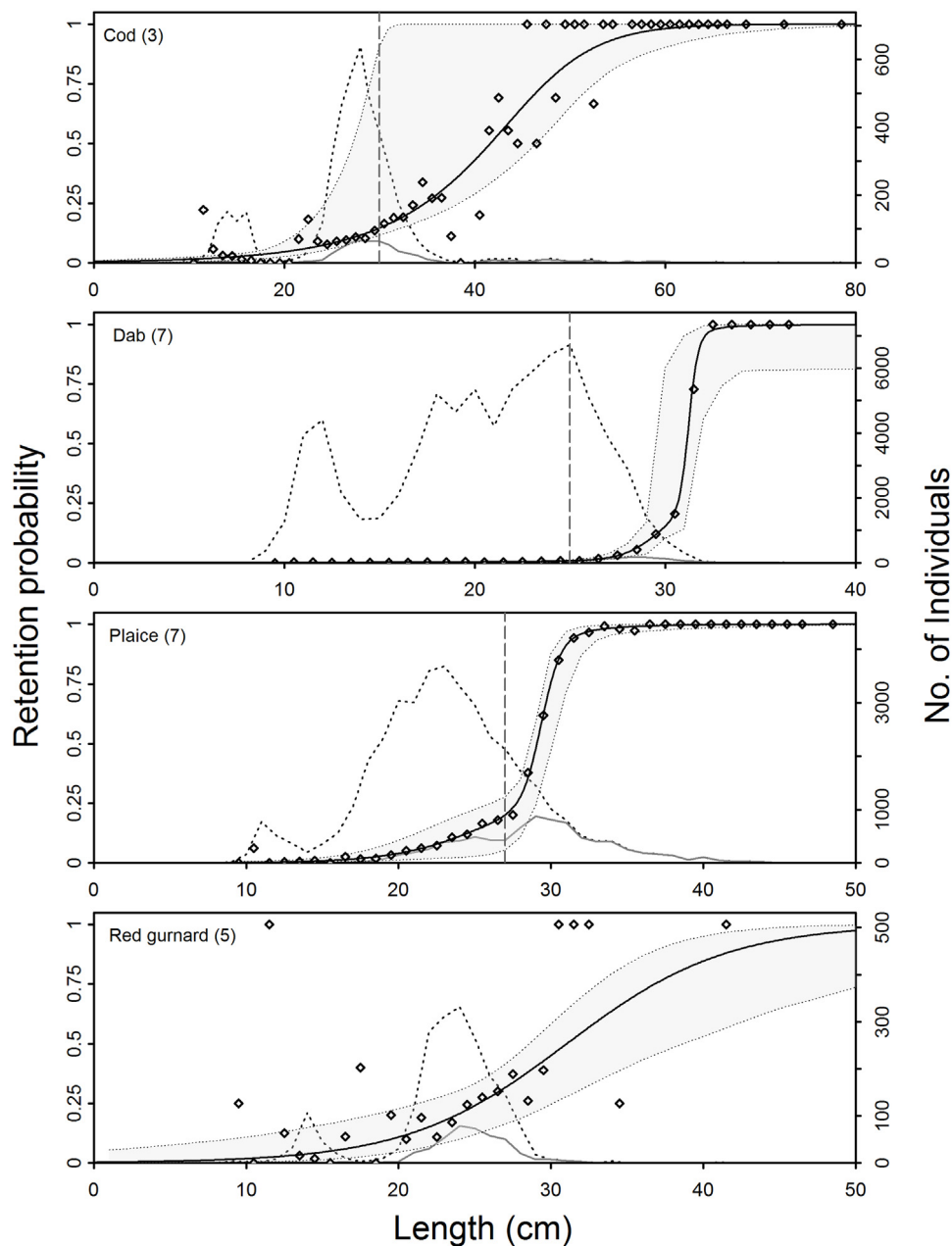
Species	SF – present study Danish seine	SF – former studies	
		Scottish seine	Trawl
Cod	3.4	3.2 (2.0–3.8) 1,2	2.4 (1.6–3.4) 1,3,4,5,6,7,8
Plaice	2.3	–	2.2 (2.0–2.3) 5,6,7,8

<sup>1</sup>Reeves et al., 1992; <sup>2</sup>Isaksen and Lokkeborg, 1993; <sup>3</sup>Graham et al., 2004; <sup>4</sup>Madsen and Stæhr, 2005; <sup>5</sup>Frandsen et al., 2009; <sup>6</sup>Frandsen et al., 2010b; <sup>7</sup>Frandsen et al., 2011; <sup>8</sup>Madsen et al., 2012.

catches were low, especially for larger length classes. This resulted in wide confidence limits of L50 and SR for cod as well as for red gurnard. Therefore, the SF values estimated for cod (3.4), which were on average similar to Scottish seines (3.2), but higher than for trawls (2.4; Table 4), should be used with caution. Future studies should focus on providing stronger selectivity estimates for cod and other species that can grow to sizes that are within the selective area of the gear.

Plaice is the most important species in the Danish seine fishery and, as it is also the case for cod, retention probabilities of small individuals were relatively high. The selectivity curve for plaice indicated a mismatch between the curve and the current MLS, which means that some plaice below MLS were retained. The estimated SF value for Danish seines (2.3) was slightly higher than the mean value of previous trawl studies (2.2), but within their range (2.0–2.3; Table 4). This indicates similar amounts of fish below MLS (MCRS) being caught by both gears, which would be discarded today. Although discarded plaice may survive (van Beek et al., 1990), they will have to be brought to land within the landing obligation system and catches will be deducted from the fishermen's quota. However, earnings of these smaller fish are likely low as it will be prohibited to sell fish below MCRS for direct human consumption. The current results would indicate potential consequences of the upcoming landing obligation system in terms of catches of smaller plaice to be relatively similar for Danish seiners and trawlers in this area. Uhlmann et al. (2014), however, reported generally lower discard rates for Danish seiners than for trawlers in the Skagerrak/North Sea and other European waters, indicating that in general lower amounts of fish below MLS (MCRS) are caught by the Danish seine fishery. Considering the results of this more general study, the consequences of the change to the landing obligation system are likely to be more pronounced in the trawl fishery. Expectable expenditures are, for instance, the separation of the less





**Fig. 4.** Selectivity curves for fish including 95% confidence intervals (grey shaded areas), length-specific retention rates (white diamonds), current species-specific MLS if available (vertical stippled line), and length distributions (stippled line: total; solid line: codend). Numbers in parentheses indicate number of hauls used for analysis (i.e. those that had > 10 measured individuals).

valuable catch from the catch with fish above MRCs, the storing of the less valuable part of the catch on board (Sardà et al., 2015) and ultimately the sale of it. As retention probabilities for fish below MLS (MCRS) are similarly high, cod may also become a problematic species within the landing obligation system, but, indicated by the smaller average SF value, consequences may again be more pronounced for bottom trawlers. Expenditures in terms of catches of dab and red gurnard are likely to be low as retention probabilities for dab below MLS (MCRS) are very low and red gurnard will still be permitted to be thrown back to sea as it is not part of the list of species that are prohibited to be discarded within the landing obligation.

The selectivity of the two species with the strongest data, dab and plaice, was best described by models indicative of a multiple selection process. Similar models have so far been used when

considering the selectivity process in trawling to consist of two or more processes, e.g. when separating the process into towing phase and haul-back phase (Herrmann et al., 2013a) or when using selective devices in addition to the codend (Kvamme and Isaksen, 2004; Sistiaga et al., 2010; Herrmann et al., 2013b). Various factors (e.g., mesh opening or tension in the codend meshes) may, however, affect selectivity characteristics during the fishing process of Danish seining in a similar way and could result in multiple selection processes. For example, increasing hauling speed over time may result in a change of the selectivity characteristics of the codend, as the increasing speed may involve more traction on the gear and on the meshes. The video recordings, however, indicated that most fish entered the seine late during the capture process, thus the number of escapees in the period of slow speeds should be low. Herrmann et al. (2015) suggested that taking the catch from a Scottish seine

aboard in several batches leaves fish in the codend and extension, where they may be subjected to tightening and relaxing meshes due to wave movement. This could cause a constant switch from stiff to slack meshes, which in turn could change selectivity characteristics at the surface and between the underwater and surface parts of the fishing process. However, catches in the current study were small enough to lift on board at once in most cases. Slack meshes may also occur when the seine ropes are retrieved and the seine needs to be stopped in order to be detached from the ropes and attached to the net drum for final retrieval. In contrast to a trawler, a Danish seiner is anchored at this time, and this stop leads to a complete standstill of the gear. Slack meshes in combination with lively fish that are in the seine for only a short period compared to fish in a trawl may explain the observed multiple selection in the Danish seine fishery. Therefore, more complex models that include dual or multiple models should be considered when describing selectivity of a Danish seine. Such approaches may result in different selectivity curves or different selectivity parameter estimates compared to those generated by the more traditional logistic models (Herrmann et al., 2016).

The selectivity estimates generated in this study provide some initial information about several fish species for which selectivity data have not been collected previously for Danish seines (all species) or any other fishing gears (dab, red gurnard). This information is important for assessing the ecosystem effects of fishing gears, for reference when issuing certificates for sustainable fisheries, and for evaluating the EU landing obligation system which requires the entire catch of listed species to be counted against a quota. To gain more knowledge about species that were observed in too few amounts within this study, more experiments need to be conducted, whereby it may be necessary to use non-commercial codends with smaller mesh sizes to retain more individuals in the codend.

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## **Paper 3**



# Estimating unaccounted selectivity for fish and invertebrates in a Danish anchor seine

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## Abstract

Current management strategies aim at assessing the impacts that different fishing gears have on target as well as non-target species. Although the codend is generally presumed to be the place where the main selectivity of fish occurs in towed fishing gears, other parts of the net have been found to contribute to the selectivity process of several invertebrate species. This means that conventional selectivity or survival studies may ignore the selectivity of other net parts than the codend for certain species. By attaching 12 small meshed collecting bags to different parts of a Danish anchor seine net and conducting normal commercial fishing activities, this study showed that there is a substantial interaction between fish and (especially) invertebrates and the forward parts of the seine net. For seven species of demersal fish, most fish escaped through the lower panel close to the codend. All invertebrate species were found in higher numbers in the collecting bags than in the codend where many organisms escaped in the lower panel of the wings or the belly. Mean levels of visible damage ranged from 1.00 to 3.25 for collected invertebrates and were similar for all gear parts. Common starfish (*Asterias rubens*), however, showed highest damage in the extension part of the net.

**Keywords:** Damage index, Ecosystem effects, Sea bed impacts, Selectivity, Skagerrak, Unaccounted mortality

## Introduction

The codend is the part of towed fishing gears where the catch is collected and where the main selection of fish occurs (Wileman *et al.*, 1996). Therefore, most studies on towed fishing gears, e.g., selectivity studies on trawls (e.g., Reeves *et al.*, 1992; Graham *et al.*, 2004; Frandsen *et al.*, 2010) or Danish anchor seines (e.g., Herrmann *et al.*, 2016; Noack *et al.*, 2017), or survival studies (e.g., Bergmann and Moore, 2001; Uhlmann *et al.*, 2016), focused on the individuals in or escaping from the codend. Previous studies on the selectivity of commercially valuable crustaceans in different types of trawls, however, found that a substantial part of the selection of Norway lobster (*Nephrops norvegicus*; Hillis and Earley, 1982), brown shrimp (*Crangon crangon*; Polet, 2000) and Antarctic krill (*Euphausia superba*; Krag *et al.*, 2014a) takes place in the forward parts of a trawl net. It may be expected that other invertebrates (Wileman *et al.*, 1996) and possibly some fish species show similar patterns in towed fishing gears. Such trawl-body selectivity cannot be seen and is not considered in studies that are limited to the codend. Therefore, the magnitude of such escape and the potential damage to individuals caused by interactions with the fishing gear remain unaccounted for in standard selectivity and survival studies.

There is an increased focus on expanding the understanding of how various types of fishing affect the marine ecosystem during their deployment (Fulton *et al.*, 2014). This highlights the need to gather information on different fishing methods, including Danish anchor seining which is considered to be a fuel-efficient fishing method (Thrane, 2004; Suuronen *et al.*, 2012) with low environmental impacts compared to other demersal fishing gears (Suuronen *et al.*, 2012; Eigaard *et al.*, 2015) that delivers high quality catches (Dreyer *et al.*, 2008; Suuronen *et al.*, 2012). One example of integrating the ecosystem effects of different fishing gears into management strategies is the current EU Common Fisheries Policy (Zhou *et al.*, 2010) which aims at assessing and reducing potential negative impacts from fishing gears on the marine habitat. An assessment of unaccounted selectivity is therefore important, particularly if these unobserved interactions can lead to unaccounted mortality.

The escape of animals from a Danish seine may vary in numbers, sizes and between species in the different gear parts, e.g., because the fishing process is partly asymmetrical and the numbers

of animals entering each side of the gear are likely to be different (Wileman *et al.*, 1996). To account for this in this study, the net of a Danish seine was divided into different parts which were strategically covered with small mesh bags. This setup was used under the commercial conditions of Danish seining in Danish waters to collect escaping fish and invertebrates throughout the gear. To quantify the effects of net interaction and escape on the collected animals, damage was assessed for all caught invertebrates. This served as a measure to indicate potential mortality and to compare selectivity and damage in the different parts of the seine net.

## Material and Methods

### *Study site and experimental setup*

Experimental fishing was carried out with the commercial Danish seiner HG 35 *Vendelbo* (length overall: 15.47 m, engine power: 91 kW) in August and September 2014. All hauls were carried out off the coast of Denmark in Skagerrak (ICES area IIIa; Figure 1). As commercial Danish seining is not only conducted in sandy flatfish areas close to the coast (e.g., for plaice *Pleuronectes platessa*), but also on deeper whitefish grounds (e.g., for haddock *Melanogrammus aeglefinus* and cod *Gadus morhua*), this study was conducted in both area types (Figure 1).

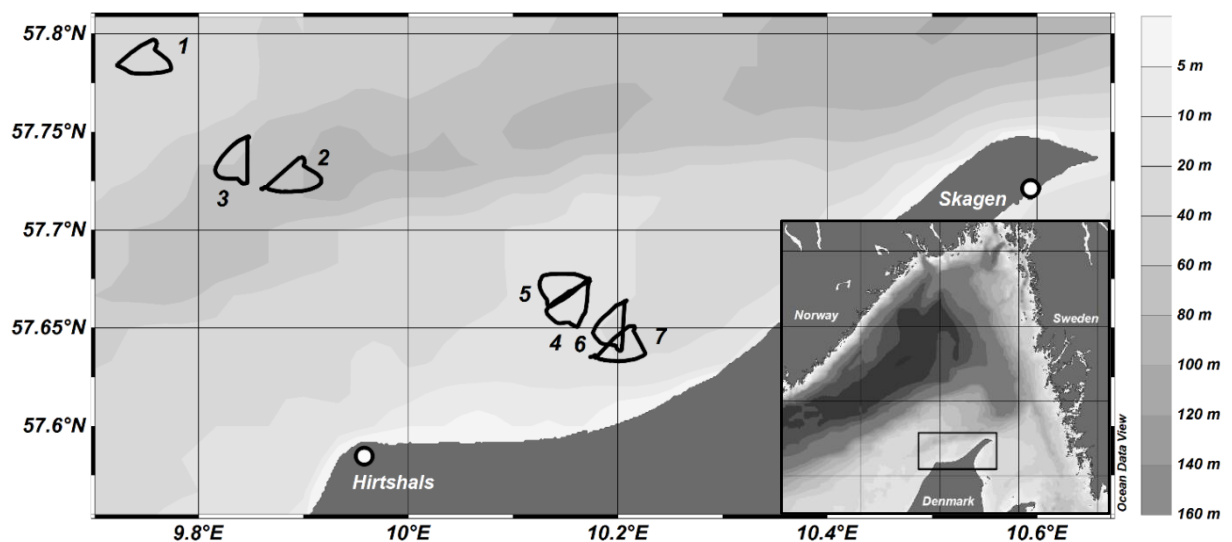


Figure 1. Area and vessel tracks for the seven hauls conducted on board the HG 35 Vendelbo in 2014.

Twelve small mesh collecting bags (Figure 2) were attached to different parts of the vessel's seine net (for vessel and gear specifications, see Noack *et al.* (2017)). Each collecting bag was 4.8 m long (stretched) and covered  $\sim 0.5 \text{ m}^2$  of the seine netting (55 - 121 meshes, depending on mesh size and mesh configuration of the specific net part). As the global geometry of a Danish seine changes considerably during the fishing process, we expected the netting characteristics of the different net parts to do the same. Due to the size of the seine net, such effects could not be experimentally tested in a flume tank. The collecting bags were therefore mounted with the aim of covering the same area of netting without distorting the seine during any stages of the fishing process. Collecting bags that were attached to the wings (bags 1-8) were not modified with weight or floats as a sufficient opening of those was expected to be achieved by the angle of the wings in relation to the towing direction. The collecting bags that were attached to the belly and the extension part of the net were expected to potentially mask the netting of the seine part they covered. To account for this, the two collecting bags in the upper panel of belly and extension (bags 9 and 11, Figure 2C) were equipped with four floats and a lead rope was attached to the two collecting bags in the lower panel (bags 10 and 12, Figure 2D) to prevent masking. To assess their performance, two underwater video cameras (GoPro Hero 3+) were attached close to collecting bag 9 in the upper panel and collecting bag 10 in the lower panel in haul 1 and 7.

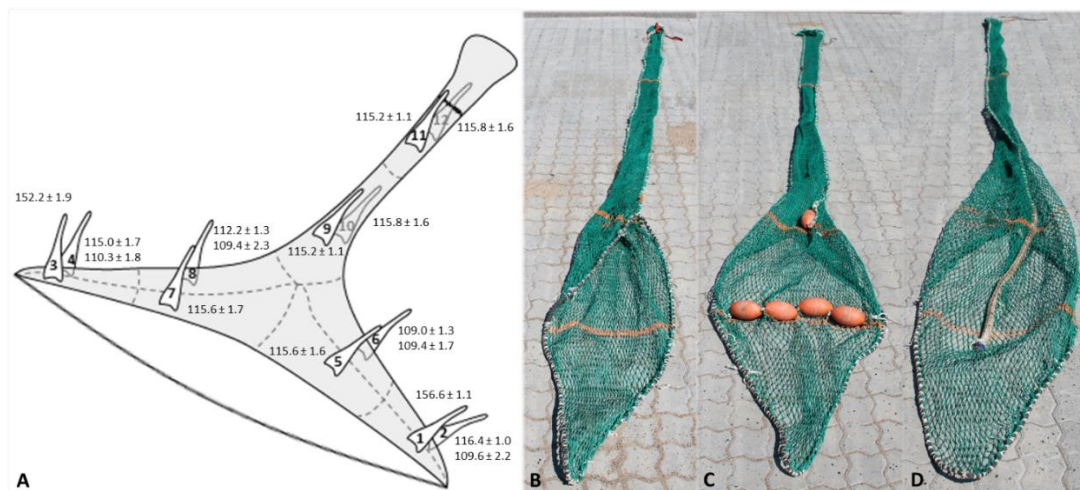


Figure 2. Collecting bags. A. Approximate locations, where bags were attached to seine net including mesh size in mm of the netting that was covered by the collecting bag ( $\pm$  standard deviation). B. Standard bag (1-8). C. Upper bag with additional floats (9+11). D. Lower bag with additional lead-filled rope (10+12).

### *Data collection and sampling strategy*

Fishing time, anchor depth and depth at the position where the net was deployed were recorded as well as sea state following the protocol of Wileman *et al.* (1996). Vessel movement during the fishing process was tracked for each haul, using a GPS-logger (Canmore G-PORTER GP-102+). After each haul, fish and invertebrates were separated, fish were measured to the nearest cm below and individual weights were estimated using length weight relationships (Coull *et al.*, 1989). All invertebrates were frozen until treated further on land where they were identified, counted, length measured to nearest mm and weight measured to nearest mg. Length measurements differed from species to species, based on their body shape (see Table 1 for details). Additionally, a damage index based on Veale *et al.* (2001) was applied to each individual, whereby levels depended on individual species characteristics (Table 1). The lowest level of damage for sessile organisms (Porifera and Anthozoa) was set to “Level 3”, because detaching sessile organisms from their substrate was also considered a damage which reduced their chance of surviving the interaction with the fishing gear. Due to large codend catches, catches of plaice were subsampled within the first three hauls (range of subsampling factor: 0.07 – 0.70) following the guidelines of Gerritsen and McGrath (2007).

Table 1. Length key and damage key (modified from Veale et al. (2001); the higher the more damage) for invertebrate species, ordered by taxonomic class.

Class	Species	Length measurement	Damage index				
			1	2	3	4	5
Asteroidea	Common starfish ( <i>Asterias rubens</i> )	maximum extent	no visible damage	- 1 arm	-2 arms	-3 to -4 arms	no arms
	Sand star ( <i>Astropecten irregularis</i> )	maximum extent	no visible damage	- 1 arm	-2 arms	-3 to -4 arms	no arms
Malacostraca	Spiny starfish ( <i>Marthasterias glacialis</i> )	maximum extent	no visible damage	- 1 arm	-2 arms	-3 to -4 arms	no arms
	Edible crab ( <i>Cancer pagurus</i> )	carapace width	no visible damage	-1 to -2 legs	-3 to -4 legs	-5 or more legs	broken carapax
	Brown shrimp ( <i>Crangon crangon</i> )	carapace length	no visible damage	-1 to -2 legs	-3 to -4 legs	-5 or more legs	broken carapax
	Sandy swimming crab ( <i>Liocarcinus depurator</i> )	carapace width	no visible damage	-1 to -2 legs	-3 to -4 legs	-5 or more legs	broken carapax
	Norway king crab ( <i>Lithodes maja</i> )	carapace length	no visible damage	-1 to -2 legs	-3 to -4 legs	-5 or more legs	broken carapax
Bivalvia	Common spider crab ( <i>Macropodia rostrata</i> )	carapace length	no visible damage	-1 to -2 legs	-3 to -4 legs	-5 or more legs	broken carapax
	Hermit crabs ( <i>Pagurus</i> spp.)	maximum shell extent	no visible damage	gentle	out of shell, intact	out of shell, not intact	broken carapax
	Prickly cockle ( <i>Acanthocardia echinata</i> )	maximum extent	no visible damage	gentle	medium	strong	irreparable
Gastropoda	Horse mussel ( <i>Modiolus modiolus</i> )	maximum extent	no visible damage	gentle	medium	strong	irreparable
	Queen scallop ( <i>Aequipecten opercularis</i> )	maximum extent	no visible damage	gentle	medium	strong	irreparable
	Common whelk ( <i>Buccinum undatum</i> )	maximum extent	no visible damage	gentle	medium	strong	irreparable
	Red whelk ( <i>Neptunea antiqua</i> )	maximum extent	no visible damage	gentle	medium	strong	irreparable
Other	Purple heart urchin ( <i>Spatangus purpureus</i> )	maximum extent	no visible damage	gentle	medium	strong	irreparable
	Sea mouse ( <i>Aphrodite aculeata</i> )	maximum extent	no visible damage	gentle	medium	strong	irreparable
	European squid ( <i>Loligo vulgaris</i> )	maximum extent	no visible damage	gentle	medium	strong	irreparable
	Crevice brittlestar ( <i>Ophiopholis aculeata</i> )	maximum extent	no visible damage	- 1 arm	-2 arms	-3 to -4 arms	no arms
	Sponges ( <i>Porifera</i> )	maximum extent	-	-	no visible damage	medium	strong
	Sea anemones ( <i>Actinaria</i> spp.)	maximum extent	-	-	no visible damage	medium	strong



## *Data analysis*

After providing individual haul information, hauls from the two area types were pooled to provide a combined picture for the areas where Danish seiners fish commercially. The seven hauls conducted did not allow separate analyses between the two areas as caught numbers of individuals in the collecting bags were relative low. Numbers of individuals in the collecting bags were raised to a value indicating how many individuals passed through the netting of the respective part of the gear using a raising factor (number of meshes covered by bag/number of meshes in gear part) ranging from 0.01 to 0.07. Graphical catch distributions of fish and invertebrates were made based on raised values showing both absolute and relative catch numbers in the collecting bags. Besides numbers of individuals, average sizes (mean  $\pm$  standard deviation) of the animals observed in the collecting bags are given. Due to low numbers of individuals per single bag, values were pooled for the “upper collecting bags” (collecting bags 1, 3, 5, 7, 9, 11) and the “lower collecting bags” (collecting bags 2, 4, 6, 8, 10, 12). Hermit crabs (*Pagurus* spp.), which lost their shell, as well as sea stars without any arms were excluded from this part of the analysis as a proper length measurement was not possible for those. A one-way analysis of variance (ANOVA) with gear part as fixed factor followed by a Tukey-HSD test was used to test for significant differences between mean length of the caught organisms in the different gear parts (significance level  $\alpha \leq 0.05$ ).

The raised numbers of fish and invertebrates in the individual collecting was used for creating Multidimensional Scaling (MDS) plots (Kruskal and Wish, 1978; Jaworska and Chupetlovska-Anastasova, 2009), where catch similarities between the collecting bags are presented based on their Euclidean distance (Kruskal and Wish, 1978). The stress value of the plot reflects the difference between the input proximities and the output distances in the n-dimensional map (Jaworska and Chupetlovska-Anastasova, 2009), and represents the goodness of fit (Kruskal and Wish, 1978). Stress values  $\leq 0.1$  were considered excellent and values  $\geq 0.15$  as not tolerable (Kruskal and Wish, 1978). For a detailed explanation of the mathematical bases of MDS, see Davison and Sireci (2000).

Finally, visual damages were registered and the damage indices of the caught invertebrates were compared between the gear parts. This part was restricted to species observed in at least two different gear parts. A one-way analysis of variance (ANOVA) with gear part as fixed factor followed by a Tukey-HSD test was used for each species to test for significant differences between damage levels in the different gear parts (significance level  $\alpha \leq 0.05$ ).

All analyses were done using R Statistical Software (Core Team, 2012) and the “MASS” package (Venables and Ripley, 2002) to conduct MDS analyses.

## Results

### *Haul overview*

Seven valid hauls with durations ranging from 131 to 180 min were conducted (Table 2). The hauls were carried out in depths between 12.8 and 73.2 m and covered an area ranging from 2.6 to 3.5 km<sup>2</sup>. Codend catches ranged from 94 to 2172 kg per haul. The sum of catches in the collecting bags ranged from 0.5 to 2.4 kg per haul. Inspection of underwater recordings showed that the floats attached to the collecting bags in the upper panel and lead lines attached to the collecting bags in the lower panel worked as intended as the bags did not mask the meshes of the seine net (Figure 3).

Table 2. Haul overview. Duration describes time from setting anchor until gear is retrieved onboard. Depth is given for position where anchor was set and where the seine was deployed. Sea state as described in Wileman et al. (1996).

Haul	Date	Duration (min)	Covered area (km <sup>2</sup> )	Depth (m)		Sea state	Total catch (kg)	
				Anchor	Seine		Codend	Collecting bags
1	23.08.2014	145	3.44	32.9	34.7	5	576.4	0.5
2	26.08.2014	151	3.42	69.5	73.2	2	2172.4	0.5
3	26.08.2014	135	3.17	42.1	54.9	2	860.1	2.4
4	27.08.2014	166	3.52	15.2	15.2	3	135.2	1.0
5	27.08.2014	160	3.13	15.2	15.7	2	94.1	0.5
6	27.08.2014	131	2.60	18.3	12.8	1	260.7	0.6
7	28.08.2014	180	3.17	18.3	13.7	2	370.6	0.9

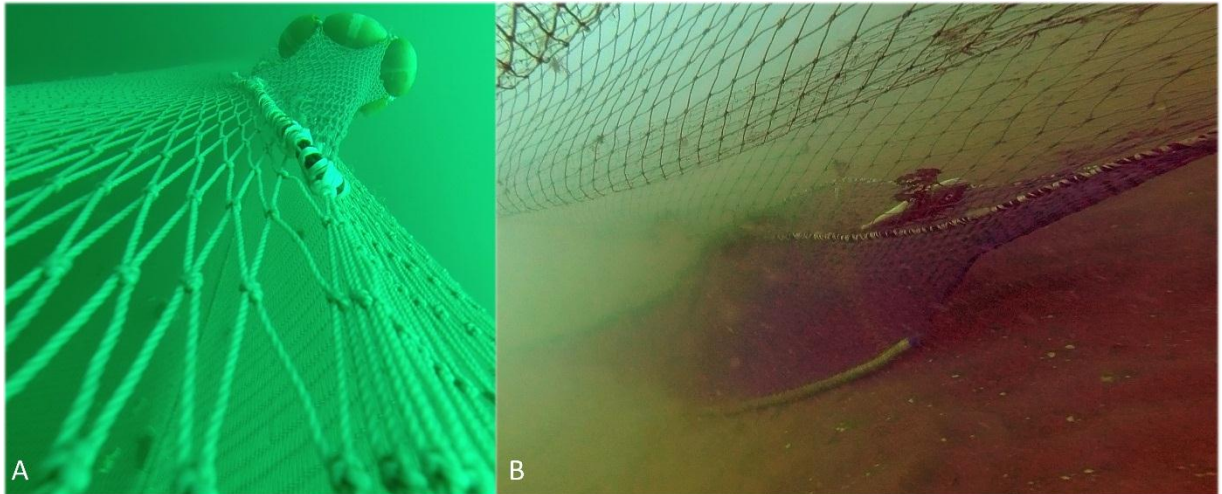


Figure 3. Examples of underwater observations, here collecting bags 9 (A; taken in final phase of haul 1) and 10 (B; taken in Haul 7 shortly before vessel returned to the anchor) showing that floats and lead rope functioned well in order to keep bags opened.

### *Catches of fish*

A higher diversity of fish species was observed in the codend than in the collecting bags (bags: 14 species, codend: 21 species, total: 26 species) and nine species were observed in both codend and at least one of the collecting bags (cod, dab *Limanda limanda*, flathead grey mullet *Mugil cephalus*, grey gurnard *Eutrigla gurnardus*, lemon sole *Microstomus kitt*, plaice, red gurnard *Chelidonichthys cuculus*, sole *Solea solea* and whiting *Merlangius merlangus* (Table 3)). For all of them, except for plaice and red gurnard, the number of fish in the codend was lower than the sum of the raised numbers in the collecting bags (Table 3). The number of individuals escaping through meshes in the wings was very low but increased towards the codend (Table 3). As also shown in Figure 4, the number of individuals was considerably higher in bags from the lower panel. Only herring (*Clupea harengus*), sprat (*Sprattus sprattus*) and whiting escaped to a large extent through the upper panel in the aft part of the seine net. Differences in the horizontal plane were minor (Table 3, Figure 4). The MDS plots of fish (Figure 5; stress values  $\ll 0.1$ ) created three main clusters; one cluster represented bag 11, one cluster combined bag 10 and 12 and one cluster combined all other bags. In the cases of dab and plaice, individuals in the upper bags were significantly larger than in the lower bags (Table 3)

Table 3. Catch overview for fish species with number of individuals observed in respective bags (raised number, representing the expected escapee number of the whole gear part in brackets) and codend. Average length  $\pm$  standard deviation is given combined for all upper bags, combined for all lower bags and for codend. Mean values that are not sharing a letter (a, b, c) are significantly different (two-way ANOVA and post-hoc Tukey-HSD test;  $\alpha \leq 0.05$ ).

Species	Individual numbers (raised to gear part)													Average size $\pm$ SD (cm)	
	Collecting bags (% , the single bags represent of whole gear)													Codend	
	1 (3%)	2 (4%)	3 (3%)	4 (4%)	5 (3%)	6 (4%)	7 (3%)	8 (4%)	9 (14%)	10 (14%)	11 (15%)	12 (10%)	Bags (up)	Bags (low)	
Brill	-	-	-	-	-	-	-	-	-	-	-	-	6	-	
Cod	-	-	-	-	-	-	-	-	-	1 (100)	-	1 (50)	104	-	
Common dragonet	-	-	-	-	-	-	-	-	-	3 (300)	-	-	0	-	
Dab	-	1 (50)	-	1 (50)	1 (20)	1 (33)	4 (57)	-	-	14 (1400)	-	31 (1550)	776	-	
Flathead grey mullet	-	-	-	-	-	1 (33)	-	-	-	-	-	1 (50)	1	-	
Flounder	-	-	-	-	-	-	-	-	-	-	-	-	21	-	
Grey gurnard	-	-	-	1 (50)	-	-	-	-	-	3 (300)	-	3 (150)	22	-	
Haddock	-	-	-	-	-	-	-	-	-	-	-	-	2	-	
Hake	-	-	-	-	-	-	-	-	-	-	-	-	3	-	
Herring	-	-	-	-	-	-	-	-	-	-	13 (1300)	-	0	-	
Lemon sole	-	1 (50)	-	-	-	-	-	-	-	-	-	7 (350)	8	-	
Lesser spotted dogfish	-	-	-	-	-	-	-	-	-	-	-	-	1	-	
Ling	-	-	-	-	-	-	-	-	-	-	-	-	1	-	
Long rough dab	-	-	-	-	-	-	-	-	-	-	-	-	4	-	
Mackerel	-	-	-	-	-	-	-	-	-	-	-	-	1	-	
Plaice	-	-	-	-	6 (120)	5 (167)	-	2 (67)	-	5 (500)	-	4 (200)	15188	-	
Pogge	-	-	-	-	-	-	-	-	-	-	-	-	1	-	
Red gurnard	-	-	-	-	-	-	-	-	-	1 (100)	-	-	394	-	
Scaldfish	-	-	-	1 (50)	-	-	-	-	-	-	-	-	0	-	
Sculpins	-	-	-	-	-	-	-	-	-	-	-	-	4	-	
Sole	-	-	-	-	-	-	1 (33)	-	-	-	-	-	1	-	
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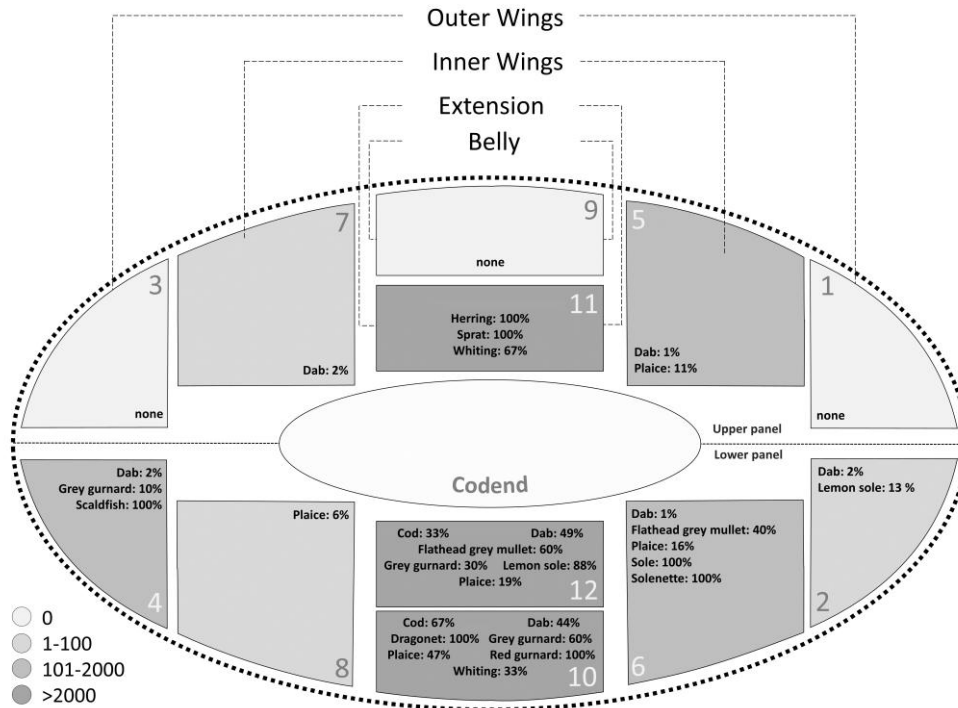


Figure 4. Raised individual numbers of fish species separated by gear part. Number in fields represents bag number, shade indicates absolute total number of individuals in the specific bag and percentage value indicates relative frequency of each species in all collecting bags.

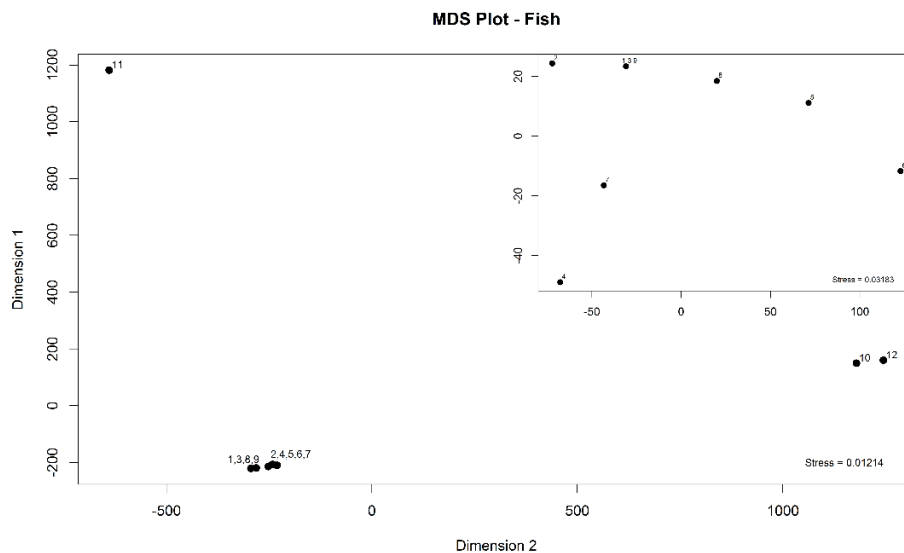


Figure 5. Multidimensional Scaling plots for fish. Number of each point indicates respective collecting bag number. Small plot represents results of analysis without bags 10-12 in order to better illustrate small differences between remaining bags.

### *Catches of invertebrates*

Twelve of twenty caught invertebrate species were found in the collecting bags and 15 species were found in the codend (Table 3). For species that were observed in both codend and at least one collecting bag (common starfish *Asterias rubens*, common whelk *Buccinum undatum*, hermit crabs, red whelk *Neptunea antiqua*, sand star *Astropecten irregularis*, sandy swimming crab *Liocarcinus depurator*, sponges *Porifera* spp.), the sum of raised numbers from the collecting bags was higher than the number of individuals observed in the codend (Table 4). Numbers in the collecting bags of the lower wings and the lower aft part of the gear were similar, but only two organisms were observed in the bags of the upper panel (Table 4). More individuals were found in the collecting bags of the portside wing than in bags of the starboard wing (Table 4, Figure 5). The MDS plot (Figure 7, stress value  $\ll 0.1$ ) created a cluster for bag 10, a cluster for bag 12 and a cluster that combined bags with zero catches or only one caught individual (all bags from the upper panel). Between those, the other bags were located. Bag 2 tended furthest towards bag 10 and 12, bag 8 towards the cluster of the upper bags and bags 4 and 6 were located in between. For both species that were observed in lower and upper bags (brown shrimp, common starfish), average length was significantly higher for individuals in the upper bags (Table 4).

Table 4. Catch overview for invertebrate species with number of individuals observed in respective bags (raised number, representing the expected escapee number of the whole gear part in brackets) and codend. Average length  $\pm$  standard deviation is given combined for all upper bags, combined for all lower bags and for codend. Mean values that are not sharing a letter (a, b, c) are significantly different (two-way ANOVA and post-hoc Tukey-HSD test;  $\alpha \leq 0.05$ ).

Species	Individual numbers (raised to gear part)													Average size ± SD (cm)	
	Collecting bags (% , the single bags represent of whole gear)														
	1 (3%)	2 (4%)	3 (3%)	4 (4%)	5 (3%)	6 (4%)	7 (3%)	8 (4%)	9 (14%)	10 (14%)	11 (15%)	12 (10%)	Codend	Bags (up)	Bags (low)
Brown shrimp	-	-	-	-	-	-	-	-	-	2 (200)	1 (100)	2 (100)	0	1.1 ± 0.0 b	0.8 ± 0.1 a
Common spider crab	-	-	-	-	-	-	-	-	-	1 (100)	-	-	0	-	2.0 ± 0.0
Common starfish	-	13 (650)	-	5 (250)	-	7 (233)	1 (14)	2 (67)	-	20 (2000)	-	4 (200)	111	17.9 ± 0.0 b	10.1 ± 2.8 a
Common whelk	-	-	-	-	-	-	-	6 (200)	-	-	-	-	1	-	6.1 ± 0.4 a
Crevice brittlestar	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-
Edible crab	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-
European squid	-	-	-	-	-	-	-	-	-	-	-	-	5	-	-
Hermit crabs	-	5 (250)	-	1 (50)	-	3 (100)	-	-	-	1 (100)	-	-	97	-	5.1 ± 2.3 a
Horse mussel	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-
Norway king crab	-	1 (50)	-	-	-	-	-	-	-	-	-	-	0	-	0.8 ± 0.0
Prickly cockle	-	-	-	-	-	1 (33)	-	-	-	-	-	-	0	-	5.3 ± 0.0
Purple heart urchin	-	1 (50)	-	-	-	-	-	1 (33)	-	10 (1000)	-	-	0	-	1.1 ± 0.7
Queen scallop	-	-	-	-	-	-	-	-	-	-	-	-	3	-	-
Red whelk	-	-	-	-	-	5 (167)	-	-	-	-	-	-	16	-	6.6 ± 0.5 a
Sand star	-	22 (1100)	-	4 (200)	-	21 (700)	-	13 (433)	-	8 (800)	-	-	44	-	7.0 ± 1.1 a
Sandy swimming crab	-	4 (200)	-	6 (300)	-	5 (167)	-	4 (133)	-	14 (1400)	-	52 (2600)	101	-	3.0 ± 0.9 a
Sea anemones	-	-	-	-	-	-	-	-	-	-	-	-	6	-	-
Sea mouse	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-





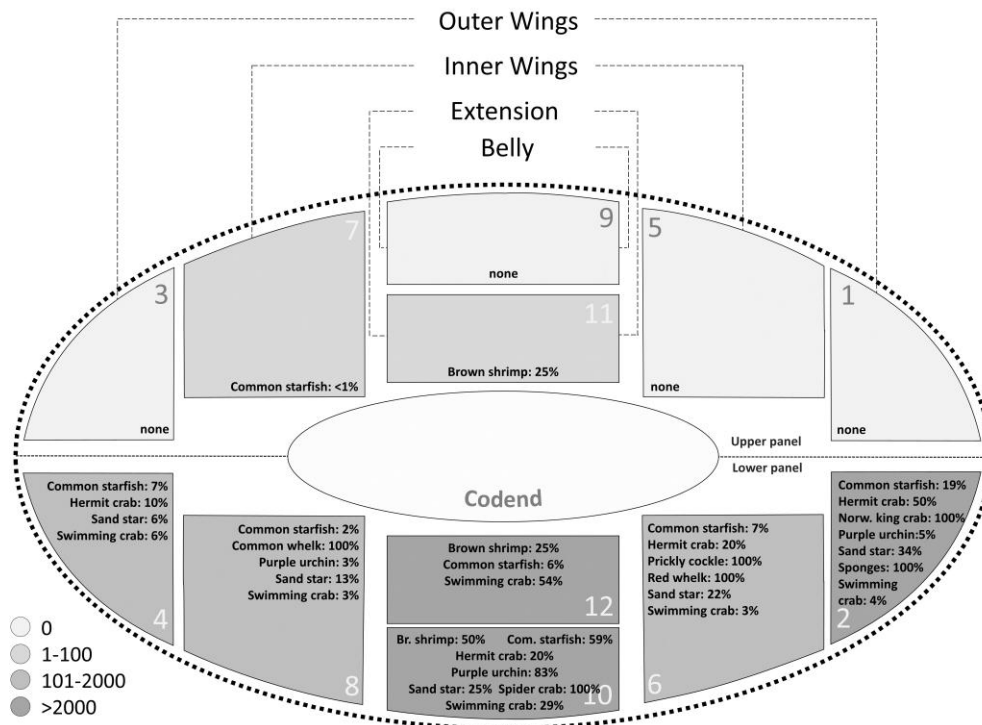


Figure 6. Raised individual numbers of invertebrate species separated by gear part. Number in fields represents bag number, shade indicates absolute total number of individuals in the specific bag and percentage value indicates relative frequency of each species in all collecting bags.

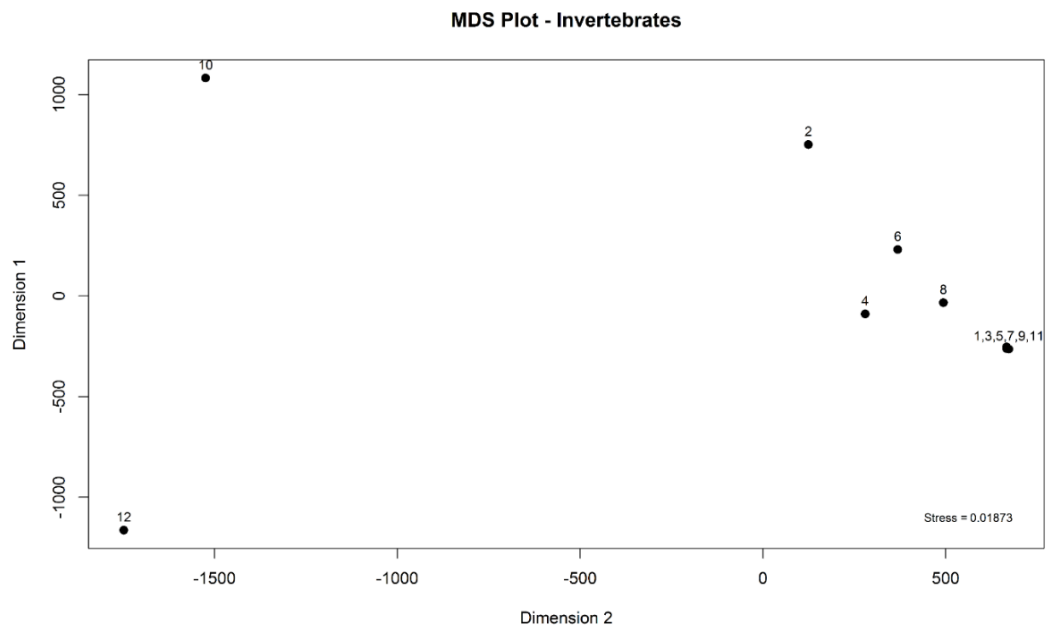


Figure 7. Multidimensional Scaling plot for invertebrates. Number of each point indicates respective collecting bag number.

### *Damage index*

Means of the estimated levels of damage ranged from 1.00 to 3.25, but were generally low for the inspected species (Table 5). Values of 2.00 were exceeded only by common starfish in the extension, by sand stars in the codend and by sponges in the inner wings and the codend (Table 5). Comparing damage indices of invertebrates was limited by the issue of unequally distributed species, allowing the comparison for only nine species (brown shrimp, common starfish, common whelk, hermit crab, purple heart sea urchin *Spatangus purpureus*, red whelk, sand star, sandy swimming crab, sponges; Table 5). Differences between the gear parts were small and significant differences were only found for common starfish having significantly higher damage levels in the extension bags than in outer wing bags and belly bags (Table 5).

Table 5. Damage levels for invertebrate species that were observed in at least two parts following levels, explained in Table 1, separated by gear part. Mean values that are not sharing a letter (a, b) are significantly different (two-way ANOVA and post-hoc Tukey-HSD test;  $\alpha \leq 0.05$ ).

Species	Compartment				
	Inner wings	Outer wings	Belly	Extension	Codend
Common starfish	1.33 a	1.65 ab	1.40 a	3.25 b	1.92 ab
Sand star	1.27 a	1.82 a	1.88 ab	-	2.91 ab
Common whelk	-	1.00 a	-	-	1.00 a
Brown shrimp	-	-	1.00 a	1.00 a	-
Sandy swimming crab	1.1 a	1.00 a	1.36 a	1.56 a	1.64 a
Red whelk	-	1.00 a	-	-	1.00 a
Hermit crabs	1.33 a	1.00 a	1.00 a	-	1.21 a
Sponges	3.00 a	-	-	-	3.00 a
Purple heart urchin	1.00 a	1.00 a	1.00 a	-	-

### **Discussion**

The results of this study clearly showed that fish and especially invertebrates interact with, and escape from, most parts of a commercial Danish anchor seine during the fishing operation. The majority of invertebrates were caught in the collecting bags mounted to the lower panel of the seine net, whereas the relatively few caught fish were primarily found in the collecting bags close to the

codend. The part of the selection in gear parts other than the codend is substantial and is currently not accounted for in conventional selectivity studies that are based on codend catches. Paired or alternate haul techniques (Wileman *et al.*, 1996) could potentially show this effect, but would not be able to describe in which part of the seine net the selectivity occurred.

However, it is important to treat the estimated numbers of escapees with care. Although the collecting bags were distributed over the entire commercial seine net, to indicate each parts' selectivity, they only covered a fraction of the part they were mounted to. More or larger small meshed collecting bags on the seine net were considered to increase the risk of affecting the commercial operation of the seine net due to extra drag. As twine characteristics, mesh sizes, mesh openings and thus the potential selectivity vary between different parts in the seine net, so does the catch in the different collection bags. The catches in the collecting bags might also be affected by considerable changes in the entire net geometry during the fishing process, starting with a loose net in the beginning that goes over a period of being overspread (high horizontal opening, low vertical opening) to a completely closed phase in the final stages of the retrieval process. Based on the conducted underwater observations, this did, however, not seem to affect the operation of the observed collecting bags.

The majority of demersal fish species escaped through the lower panel in the aft part of the gear where pelagic species like herring and sprat escaped solely through meshes in the upper panel in the aft part of the gear. Such species specific behavioral differences can be used to improve the seine net's species or size selectivity as demonstrated for trawls (Thomsen, 1993; Krag *et al.*, 2014b; Krag *et al.*, 2015).

Contrary to fish, invertebrates have limited motility. Where fish swim and actively orientate in relation to the surrounding netting to avoid contact with it (Glass *et al.*, 1993; Glass and Wardle, 1995), invertebrates are expected to roll more passively along the lower netting resulting in multiple contacts with the meshes from the net mouth and back towards the codend. The catches of invertebrates in the collecting bags indicated that most invertebrates escaped through the netting in the lower forward sections of the seine net and that only a small proportion of the invertebrates that entered the seine net ended up in the codend. The general selectivity pattern for invertebrates in seine

nets, and likely also in trawls, is therefore different from fish that primarily escape through meshes in the codend (Wileman *et al.*, 1996). This difference between fish and invertebrates can be utilized to reduce catches of unwanted invertebrates without losing fish as fish avoid contact with the forward netting parts (Glass *et al.*, 1993; Glass and Wardle, 1995). In the North Sea, for instance, benthic release panels mounted to the lower netting of beam trawls were found to successfully reduce catches of unwanted invertebrates (Revill and Jennings, 2005).

As the present study showed, codend selectivity does not reflect the entire selectivity process for invertebrates in Danish seines. Quantifying the escape of invertebrates in Danish seines or trawls, as part of a comprehensive description of active gears' interactions with the ecosystem, will require approaches similar to the current approach. The system of collecting bags makes such quantifications possible and further appeared relatively sensitive to pick up small differences between net parts. For instance, higher escape rates of invertebrates in the portside than in the starboard side of the seine net could be indicated. Due to the asymmetrical way the Danish seine is set out and dragged in the early stages of the fishing process (Wileman *et al.*, 1996), these differences were expected. Contrary to invertebrates, this asymmetrical catch tendency was not observed for fish as fish actively avoid the netting (Glass *et al.*, 1993).

The assessment of the invertebrates' damage indicated relatively low levels of visual damage, which is likely due to their robust exoskeleton or shells. Similar results have been found for trawls (Bergmann *et al.*, 2001). Higher levels of damage in aft parts than in front parts, which were observed for common starfish, indicated that a longer time and distance inside the netting results in more mechanical interaction with the netting. This means that lower damage levels can be expected if such animals could be released earlier in the process. The commercial seine net used in the current study had relative large meshes in the forward sections of the seine net (120 - 160 mm) which presumably resulted in already high numbers of escapees. In smaller mesh designs, it would be expected that the organisms require a higher contact probability with the netting to successfully escape, if physically possible. Such designs, which can be found in the *Nephrops* directed trawl designs (Krag *et al.*, 2008) may result in an increase of mechanical damages due to the increased netting contact and longer towing durations. However, the damage assessment in the current study

considered only visible external damages and conclusions of previous studies about relationships of external damages and mortality are inconsistent (Broadhurst *et al.*, 2006). Therefore, the degree of damage cannot be translated directly into mortality rates and future experiments should include survival assessments and evaluate mechanical as well as physiological damage as a proxy for survival. If it is concluded that low survival is the consequence of organisms' interaction with seines or trawls, then there is a need to develop invertebrate release systems similar to the benthic release panels used in some beam-trawl fisheries (Revill and Jennings, 2005). By applying the findings of the present study, these devices should be implemented into the front part of the gear.

### **Supplementary material**

The following supplementary material is available at ICESJMS online: Supplementary Table S1 which provides a full catch overview of all observed fish species.

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## Supplementary material

Table S1. Fish species observed within the study.

Species	Scientific name
Brill	<i>Scophthalmus rhombus</i>
Cod	<i>Gadus morhua</i>
Common dab	<i>Limanda limanda</i>
Common dragonet	<i>Callionymus lyra</i>
Flathead grey mullet	<i>Mugil cephalus</i>
Flounder	<i>Platichthys flesus</i>
Grey gurnard	<i>Eutrigla gurnardus</i>
Haddock	<i>Melanogrammus aeglefinus</i>
Hake	<i>Merluccius merluccius</i>
Herring	<i>Clupea harengus</i>
Lemon sole	<i>Microstomus kitt</i>
Lesser spotted dogfish	<i>Scyliorhinus canicula</i>
Ling	<i>Molva molva</i>
Long rough dab	<i>Hippoglossoides platessoides</i>
Mackerel	<i>Scomber scombrus</i>
Plaice	<i>Pleuronectes platessa</i>
Pogge	<i>Agonus cataphractus</i>
Red gurnard	<i>Chelidonichthys lucernus</i>
Scaldfish	<i>Arnoglossus laterna</i>
Sculpins	<i>Myoxocephalus spp.</i>
Sole	<i>Solea solea</i>
Solenette	<i>Buglossidium luteum</i>
Sprat	<i>Sprattus sprattus</i>
Turbot	<i>Psetta maxima</i>
Whiting	<i>Merlangius merlangus</i>
Witch flounder	<i>Glyptocephalus cynoglossus</i>

## **Paper 4**



# Fishing profiles of Danish seiners and bottom trawlers in relation to current EU management regulations

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## Abstract

Danish seines and bottom trawls are fishing gears that operate differently, and have different catching processes, but both belong to the same legislative category in European fisheries. This study compared both gears in terms of their fishing characteristics and their catches of commercial species based on 16 years of observer data. Danish seining was found to be a specialized fishing method that targeted few species with higher total catch rates than trawlers. Bottom trawling is a more all-purpose fishing method that can be used in most habitat types, targeted more different species and generally used larger engines than Danish seiners. A general additive mixed model indicated catch rates of flatfish to be generally higher for Danish seines and catch rates for roundfish species to be higher for trawlers. The results of the study do not suggest a separation of the two gears in terms of legislation because quantities of fish below current minimum size were similar. Expected challenges in size selectivity in relation to the landing obligation will likely be similar for both gears. However, local and seasonal conditions as well as effects of vessel and trip were found to play an important role in determining catches of both gears.

**Keywords: Common Fisheries Policy, Demersal Fishery, Discard ban, General additive mixed modelling, Landing obligation, Observer data**

## **Introduction**

Both Danish anchor seines and demersal otter trawls (hereafter referred to as seines and trawls, respectively) are core fishing gears in Denmark and other countries. Both belong also to the same legislative category of fishing gears in the European Union (EU; Council Regulation (EC) 850/98). However, this regulation has been brought into question by fishermen and other stakeholders because there are differences in the gear designs and especially the fishing procedures between seines and trawls. Initially, the seine was developed by a Danish fisherman specifically to catch flatfish, whereas trawls are more opportunistic gears in terms of target species. Today, Norway lobster (*Nephrops norvegicus* (L.)) and several fish species (roundfish and flatfish) are targeted by trawlers. However, a significant proportion of the catches of both gears is discarded (Kelleher, 2005). This happens for several reasons including minimum landing sizes (MLS), quota restrictions and high-grading (Kelleher, 2005; Feekings et al., 2012; Catchpole et al., 2013). To eliminate discards, a central part of the new Common Fisheries Policy in Europe is a landing obligation which is being introduced on a fishery-by-fishery basis (Council Regulation (EU) 1380/2013). It applies to all species “which define the fisheries”, i.e. species subject to catch limits should be landed from 1 January 2016. Full implementation of the landing obligation shall be done within three years (Council Regulation (EU) 2016/72). The landing obligation further introduces minimum conservation reference sizes (MCRS, usually equal to current MLS) where fish below this size are not allowed to be sold for direct human consumption (Council Regulation (EU) 1380/2013). The objective of this landing obligation system is to make fishermen fish more selectively (Condie et al., 2013) and to reduce bycatch instead of utilizing quota for less commercial catches (Borges et al., 2016). However, as previous studies found indications of differences in the selectivity characteristics of seines and trawls (Herrmann et al., 2016; Noack et al., 2017), portions of fish below MCRS are likely different for both gears.

The present study used data from a perennial monitoring program of commercial vessels to establish a comprehensive dataset for describing and comparing the seine and trawl fishery including their catches of commercial species, i.e. species that had a quota in 2016 and/or were directly targeted. Such information will give an insight into whether the legal grouping of seines and trawls is appropriate. Moreover, the results of the study are essential to assess the two fishing methods in relation to the new management strategy, to identify problems the fisheries will be confronted with under the landing obligation system and to suggest potential solutions for those.

## **Material and Methods**

### *Data collection and selection*

Data of the present study originated from a national observer program (until 2002) and a European discard sampling program (from 2002) in accordance with the European Data Directive (Council Regulation (EC) 1639/2001). Data were collected onboard commercial fishing vessels participating in the discard sampling programs in the period from 1997 to 2012, where all fish species as well as some invertebrates (Norway lobster and cephalopods) were measured for length. In cases when representative subsamples needed to be taken, individual numbers were raised to haul level following the standard procedure for the sampling program. Fishing practice was assumed to be unaffected by the presence of an observer and the chosen vessels and trips were assumed to be representative for the fishery in the area (Feekings et al., 2012). Further details about the Danish discard sampling program including sampling strategy and data collection have been described in Feekings et al. (2012).

The study area focused on Skagerrak and a small area in northern Kattegat (Fig. 1). Both areas form a relatively restricted region of large commercial importance, where trawlers and seiners fish under similar technical regulations, which changed several times in the past including the observed period. These changes applied to codends in seines as well as in trawls and differences between legislations in Skagerrak and Kattegat were small. Before 1989, 60 mm was the minimum codend mesh size in both areas. It was increased to 70 mm in 1989 (Kirkegaard et al., 1989) and a

mandatory square mesh panel (SMP) was introduced in 2000 (Council Regulation (EC) 850/98). From 2005, the minimum mesh size in codends was 90 mm (diamond mesh) or 70 mm (square mesh codend including a grid), respectively (Council Regulation (EC) 27/2005). Optionally, fishermen were encouraged to use a 120 mm SMP, which has been rewarded by extra sea days (Council Regulation (EC) 27/2005). In 2011, the SELTRA panel comprising of either a 270 mm diamond mesh panel or a 180 SMP was made mandatory for codend mesh sizes from 90 to 119 mm in Kattegat (Vinther and Eero, 2013). In Skagerrak, it was introduced in 2013, but with a 140 mm SMP (BEK No. 1423 of 12/12/2013) instead of 120 mm. Regardless of the changes in technical regulations during the period of the sampling program, hauls with mesh sizes below 90 mm were excluded to use only comparable mesh sizes in the analyses. Seiners never fished with these small mesh sizes, but trawlers did until the prohibition in 2005. Since codend mesh size was expected to influence catches, the dataset was divided into two equalized categories (90 - 109 mm and  $\geq 110$  mm). Although regulations and technical measures for towed gears did not only prescribe specific mesh sizes, but also additional selectivity devices like escape windows (Council Regulation (EC) 850/98), effects of those have not been taken into account in the analyses because the specification of these devices was not sufficiently documented in the dataset. The use of selective devices was expected to be similar for both gears as they are in the same gear group in the technical legislation (Council Regulation (EC) 850/98).



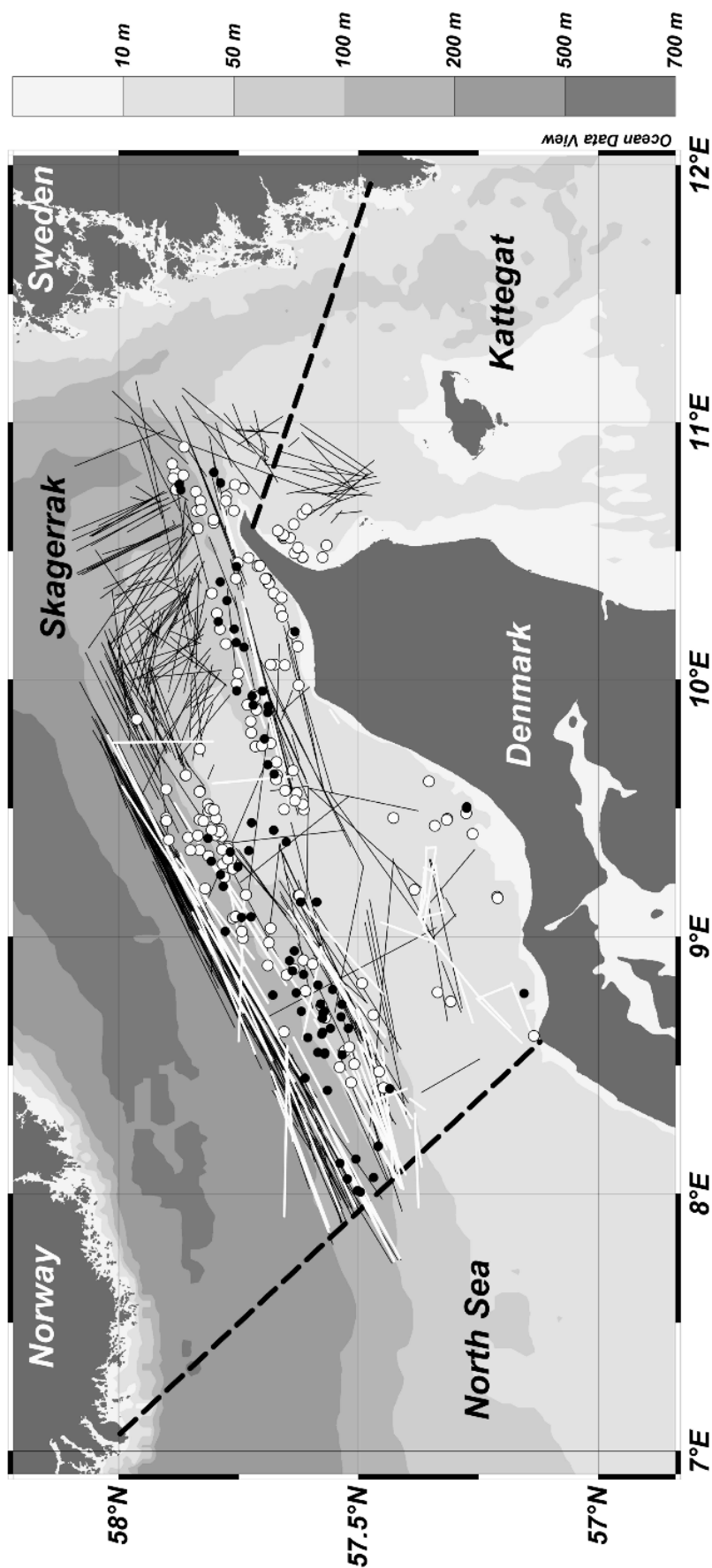


Figure 1. Study area and location of fishing operations separated by gear and mesh size category. Danish seines 90 - 109 mm (black dots as anchor points,  $n = 381$ ). Danish seines  $\geq 110$  mm (white dots as anchor points,  $n = 205$ ). Demersal otter trawls 90 - 109 mm (black lines as haul tracks,  $n = 205$ ). Demersal otter trawls  $\geq 110$  mm (white lines as haul tracks,  $n = 79$ ). Grey shading notes bathymetry of the study area.

### *Description and comparison of fishing characteristics*

The first part of the analysis was a general comparison of both fisheries including observation information (years of observation, number of observed vessels and number of observed hauls), characteristics of the fisheries (engine power, haul duration, fishing depth and target species) and general catch information (catch per haul, catch per hour). Where appropriate, values were calculated as mean values  $\pm$  standard deviation (SD) and a two-way analysis of variance (ANOVA) with gear and mesh size as fixed factors followed by a Tukey-HSD test was used to test for significant differences between the categories (significance level  $\alpha \leq 0.05$ ).

### *Description and comparison of catches*

This part of the study looked on species level into the catches of commercial species, i.e. species with quota in 2016 and/or explicitly targeted by the vessels considered within the dataset. After providing general information about the potential existence of quota in 2016 and potential minimum size (MS as either MLS or MCRS), information about occurrence (observation frequency as number of hauls with observation divided by the number of hauls in total) and total number of caught individuals within the dataset is given.

In addition, catch rates (number per hour) were calculated and a MS ratio (number of individuals below current MLS or potentially coming MCRS divided by total number of individuals per haul) was estimated for all species that have a MS. Both measures were calculated as mean values  $\pm$  SD. Testing for significant differences between the categories was done using a two-way analysis of variance (ANOVA) with gear and mesh size as fixed factors followed by a Tukey-HSD (significance level  $\alpha \leq 0.05$ ). This approach detected several significant differences between gear and mesh size categories, but  $R^2$  values were very low (Table S1, Table S2), which indicated a high unexplained deviance. To account for this and to find out which other factors than gear type and mesh size determined catch rates and MS ratios of the different species, both measurements were investigated in more detail. Models were formulated that included all additional parameters that were available from the dataset, that might be of relevance in determining catch rates and MS ratios and

that could affect catches of seiners and trawlers differently, i.e. depth, haul duration, latitude, longitude, subsampling factor, target species, trip number, vessel name, engine power, year and year quarter. Four of them (haul duration, longitude, engine power, year) had to be excluded due to collinearity with other covariates (variance inflation factors > 3; Zuur et al., 2010).

Generalized additive mixed models (GAMMs) were used to describe relationships between catch rates or MS ratios and the explanatory variables to account for the unbalanced sampling design between explanatory variables (e.g., different number of hauls for different gear categories). For the catch rate models, a Poisson distribution was assumed because catch rate represents count data, i.e. number of fish per unit of effort. Cases of overdispersion (conditional variance exceeds the conditional mean and/or presence of many zero observations) were handled using a negative binomial distribution (Zuur et al., 2009). Both distributions were applied, using a log-link function. Zero-observations were included into the analysis because they form an important part of the total observations. Conditions on different vessels may have differed due to vessel type, vessel size, skipper effects or vessel-specific sorting behaviors (Tschernij and Holst, 1999; Poos and Rijnsdorp, 2007; Feekings et al., 2013), but the data structure could be regarded as a hierarchical structure, i.e. vessel – trip – haul. Therefore, vessel and trip were always included in the model, even if the model found them to be non-significant. Furthermore, the subsampling factor was included as an offset in all models as the ratio of individuals observed and individuals measured. It was the only variable which was transformed (log-transformation).

The following was the GAMM for catch rates per haul  $i$  (Eq. 2):

Catch rate $_i \sim$  Poisson / negative binomial( $\mu_i, \sigma$ ), where

$$\begin{aligned} \log(\mu_i) = & \eta + \beta(\text{gear}_i) + \gamma(\text{mesh}_i) + \delta(\text{quarter}_i) + \zeta(\text{target}_i) + \\ & s(\text{depth}_i) + s(\text{latitude}_i) + \text{random effect (vessel}_i) + \\ & \text{random effect (trip}_i) + \text{offset (log(subsampling factor}_i)) + \varepsilon \end{aligned} \quad (1)$$

Fixed effects are the nominal covariate “gear” representing either trawl or seine, the continuous covariate “mesh” for the used numerical mesh size, the nominal covariate “quarter” for the quarters of a year, the nominal covariate “target” for the targeted species and the continuous

covariates “depth” and “latitude” representing the fishing depth and the respective north-south position. “Vessel” and “trip” as nominal covariates are random effects that represent the respective fishing vessel and trip number.  $\eta$  describes the intercept, which represents seines that fished in quarter one and targeted cod,  $s$  is an isotropic smoothing function that was used to define smooth terms (thin-plate regression spline; Wood, 2003), and  $\varepsilon$  is an error term.

For MS ratios, the procedures explained for the catch rate models were followed, but since ratios can take values between 0 and 1, a binomial distribution was used. Cases of overdispersion were handled by using a quasibinomial distribution. For both distributions, a logit-link function was applied.

The GAMM for MS ratios per haul  $i$  (Eq. 2) was:

$$\begin{aligned}
 MS\ ratio_i &\sim \text{binomial / quasibinomial } (\mu_i, \sigma), \text{ where} \\
 \text{logit}\left(\frac{\mu_i}{1-\mu_i}\right) &= \eta + \beta(\text{gear}_i) + \gamma(\text{mesh}_i) + \delta(\text{quarter}_i) + \zeta(\text{target}_i) + \\
 &s(\text{depth}_i) + s(\text{latitude}_i) + \text{random effect (vessel}_i) + \\
 &\text{random effect (trip}_i) + \text{offset (log(subsampling factor}_i)) + \varepsilon
 \end{aligned} \tag{2}$$

The following steps of model selection and model validation were the same for both models. After estimating the model, the least significant covariate with largest p-value was removed and the new model was applied again. If there were non-significant results in the categorical terms (quarter, target), levels were combined and the model was refitted. This was done until all remaining covariates except vessel and trip were statistically significant ( $p < 0.05$ ). The final model was validated by checking residuals for linearity and normality (scatterplot of residuals vs. fitted values and histogram), spatial independence (xy-plot of residuals vs. position as spatial factor) and still existing patterns in relation to covariates (xy-plot of residuals vs. remaining covariates). Outliers were identified in the original data and further examined, but no observations were removed since no oddities were found. Results are shown for all models, which passed all steps of the validation process.

All analyses were done in R Statistical Software (R Core Team, 2015), using the package “mgcv” (Wood, 2011) to conduct general additive mixed modelling.

## Results

### *Fishing characteristics*

The dataset consisted of 285 fully commercial hauls for seines and 460 hauls for trawls (Table 1, Fig. 1). In relative terms, more hauls by seiners were conducted using large mesh sizes, while trawlers used more often smaller mesh sizes (Table 1). Average engine power was significantly lower for seiners than for trawlers for both mesh size categories (Table 1) and mean haul duration for seiners was less than half compared to trawlers (Table 1). Areas fished by trawlers and seiners overlapped in some cases (Fig. 1), but mean fishing depth for seiners using mesh sizes  $\geq 110$  mm (“a” in Table 1) was significantly lower than for the other categories (Table 1). Mean fishing depth for seiners 90 - 109 mm (“b” in Table 1) and trawlers 90 - 109 mm (“c” in Table 1) were also significantly different, but both were not significantly different to the values for trawlers using a mesh size  $\geq 110$  mm (“bc” in Table 1). Mean total catches per haul were significantly lower for seines than for trawls, but mean catch rate for seines with mesh sizes  $\geq 110$  mm was significantly higher than for the three other categories. All target species of seiners, including plaice (*Pleuronectes platessa* L.) as the main target species, could also be found on the target list of trawlers. The list of target species for trawlers included five species that were not targeted by seines; dab *Limanda limanda* (L.), lemon sole *Microstomus kitt* (Walbaum), Norway lobster, sole *Solea solea* (L.) and turbot *Scophthalmus maximus* (L.).

Table 1. General gear comparison using mean values  $\pm$  standard deviation including dfs (degrees of freedom) and adjusted  $R^2$  as measure of explained deviance. Mean values that are not sharing a letter (a, b, c) are significantly different (two-way ANOVA and post-hoc Tukey-HSD test;  $\alpha \leq 0.05$ ). Target species (according to skipper) describe species targeted by the different gear categories in descending order, number in parenthesis reflects number of hauls targeting this species.

	90 - 109 mm		$\geq 110$ mm		dfs	adj. $R^2$
	Seine	Trawl	Seine	Trawl		
Years	11	16	14	11	-	-
Vessels (no.)	11	55	22	19	-	-
Engine power (kW)	214.9 $\pm$ 90.0 a	404.4 $\pm$ 194.1 b	169.6 $\pm$ 105.2 a	457.2 $\pm$ 265.5 b	741	0.30
Hauls (no.)	80	381	205	79	-	-
Haul duration (min)	172.0 $\pm$ 23.9 a	369.7 $\pm$ 101.2 b	154.7 $\pm$ 35.9 a	356.2 $\pm$ 101.6 b	741	0.60
Fishing depth (m)	75.1 $\pm$ 39.2 b	109.2 $\pm$ 68.1 c	52.4 $\pm$ 38.0 a	92.3 $\pm$ 67.5 bc	739	0.15
Catch per haul (kg)	464.9 $\pm$ 320.1 a	879.9 $\pm$ 589.6 b	700.5 $\pm$ 772.5 a	1151.4 $\pm$ 1527.3 c	741	0.05
Catch per hour (kg)	161.4 $\pm$ 111.2 a	146.9 $\pm$ 93.8 a	274.8 $\pm$ 294.6 b	198.0 $\pm$ 261.9 a	741	0.07
Target species (No. of hauls)	Plaice (60)	Norway lobster (222)	Plaice (103)	Plaice (37)		
	Witch flounder (8)	Cod (59)	Cod (68)	Saithe (10)		
	Cod (7)	Saithe (32)	Haddock (21)	Cod (9)		
	Haddock (5)	Plaice (26)	Witch flounder (11)	Haddock (9)		
		Witch flounder (16)	Saithe (2)	Witch flounder (4)		
		Sole (13)		Lemon sole (3)		
		Haddock (11)		Norway lobster (3)		
		Lemon sole (2)		Dab (2)		
				Turbot (2)		

## Catches

Twelve species were considered (Table 2) of which three had no quota limits in 2016 (dab, lemon sole, witch flounder *Glyptocephalus cynoglossus* (L.)) in the study area, but were directly targeted by some vessels. Nine of these species are subject to MS regulations, where the MRCS of Norway lobster is different to the former MLS and the MS of witch flounder is only legal on a national level in some countries (Table 2). All species were observed in both gear types and mesh categories, but occurrences of herring, Norway lobster and Norway pout were low in Danish seines (Table 2).

Table 2. Species overview including information about potential existence of quota in 2016, potentially existing minimum size, total number of observed individuals and occurrence (ratio of hauls with observation to total number of hauls) separated by gear (seine (S) and trawl (T)) and mesh size categories (in mm).

Species	Scientific name	Quota	Minimum size	Individuals	Occurrence (%)			
					90 - 109		≥ 110	
					S	T	S	T
Cod	<i>Gadus morhua</i> L.	yes	30	151964	98	96	88	91
Dab	<i>Limanda limanda</i> (L.)	no	-	174856	81	46	81	67
Haddock	<i>Melanogrammus aeglefinus</i> (L.)	yes	27	154929	78	84	53	72
Hake	<i>Merluccius merluccius</i> (L.)	yes	30	13215	70	64	30	41
Herring	<i>Clupea harengus</i> L.	yes	18	6399	9	37	6	22
Lemon sole	<i>Microstomus kitt</i> (Walbaum)	no	-	24794	91	67	64	62
Norway lobster	<i>Nephrops norvegicus</i> (L.)	yes	total: 13, carapace: 4 <sup>1</sup>	1910743	1	72	1	14
Norway pout	<i>Trisopterus esmarkii</i> (Nilsson)	yes	-	13425	4	30	6	9
Plaice	<i>Pleuronectes platessa</i> L.	yes	27	498873	96	85	99	82
Saithe	<i>Pollachius virens</i> (L.)	yes	30	54705	41	60	20	56
Whiting	<i>Merlangius merlangus</i> (L.)	yes	23	46714	35	70	21	48
Witch flounder	<i>Glyptocephalus cynoglossus</i> (L.)	no	- <sup>2</sup>	65207	79	80	47	52

<sup>1</sup> new: total length: 10.5; tail length: 5.9; carapace length: 3.2

<sup>2</sup> no Minimum Landing Size (MLS) on EU level, but local MLS of 28 cm in Germany, Denmark, Scotland, Sweden and parts of England

Mean catch rates ranged from 0.0 to 971.2 individuals per hour (Norway lobster in both seine categories and in trawls 90 - 109 mm, respectively; Table 3). Regarding fish species, catch rates ranged from 0.1 (Norway pout *Trisopterus esmarkii* (Nilsson) in both seine categories) to 481.1 individuals per hour (plaice in seines ≥ 110 mm, Table 3). Catch rates for plaice and witch flounder were significantly higher in seines and for saithe and whiting in trawls (Table 4). Catch rate was

often significantly affected when Norway lobster or plaice, as main target species of the fisheries, were the targeted species (Table 4). In case Norway lobster was targeted, catch rates of Norway lobster and roundfish increased, but catch rates of flatfish decreased. If plaice was targeted, catch rates of Norway lobster and roundfish decreased, but catch rates of flatfish increased. Mesh size was significant for four species (Norway lobster, saithe, whiting, witch flounder), where catch rates decreased slightly with increasing mesh size for three of them (Table 4). Season was significant for seven species (Table 4), but the differences between the four seasons were species-dependent and no general pattern was found. Depth was found to be significant for all species and latitude was significant for seven of them (Table 4). Since latitude and depth were handled as smooth terms, a determination of the direction of impacts has not been possible here. Vessel or trip or both random effects were significant for all species except Norway pout.



Table 3. Catch rates (ind./h) and minimum size (MS) ratios (individuals below minimum landing size (MLS) or minimum conservation reference size (MCRS)/total no. of individuals)  $\pm$  standard deviation separated by gear and mesh size.

Species	Catch rate		MS ratio			
	90 - 109 mm		$\geq 110$ mm		90 - 109 mm	
	Seine	Trawl	Seine	Trawl	Seine	Trawl
Cod	47.7 $\pm$ 48.3	38.3 $\pm$ 51.9	54.2 $\pm$ 109.2	47.2 $\pm$ 64.4	0.2 $\pm$ 0.2	0.4 $\pm$ 0.3
Dab	38.3 $\pm$ 75.8	51.8 $\pm$ 127.2	74.6 $\pm$ 178.2	40.9 $\pm$ 142.1	-	-
Haddock	38.3 $\pm$ 47.5	40.9 $\pm$ 82.8	33.1 $\pm$ 76.8	62.2 $\pm$ 115.2	0.1 $\pm$ 0.2	0.4 $\pm$ 0.4
Hake	2.6 $\pm$ 5.6	5.0 $\pm$ 10.2	1.9 $\pm$ 8.0	1.1 $\pm$ 2.2	0.0 $\pm$ 0.0	0.2 $\pm$ 0.3
Herring	0.2 $\pm$ 0.7	2.5 $\pm$ 8.0	0.3 $\pm$ 2.1	1.0 $\pm$ 4.1	0.2 $\pm$ 0.4	0.1 $\pm$ 0.3
Lemon sole	14.6 $\pm$ 14.5	6.4 $\pm$ 21.1	5.1 $\pm$ 12.3	8.2 $\pm$ 14.6	-	-
Norway lobster	0.0 $\pm$ 0.2	971.2 $\pm$ 1952.0	0.0 $\pm$ 0.0	30.2 $\pm$ 153.5	0.5 $\pm$ 0.0	0.5 $\pm$ 0.3
Norway pout	0.1 $\pm$ 0.8	5.3 $\pm$ 27.1	0.1 $\pm$ 0.8	0.5 $\pm$ 2.7	-	-
Plaice	280.1 $\pm$ 689.7	60.3 $\pm$ 148.4	481.1 $\pm$ 849.7	146.1 $\pm$ 194.1	0.2 $\pm$ 0.2	0.4 $\pm$ 0.4
Saithe	2.7 $\pm$ 14.0	15.3 $\pm$ 49.1	3.9 $\pm$ 44.6	22.5 $\pm$ 82.8	0.0 $\pm$ 0.1	0.0 $\pm$ 0.1
Whiting	0.9 $\pm$ 2.2	20.8 $\pm$ 37.1	1.1 $\pm$ 4.3	4.1 $\pm$ 9.1	0.5 $\pm$ 0.4	0.4 $\pm$ 0.3
Witch flounder	33.2 $\pm$ 63.1	17.1 $\pm$ 30.7	17.4 $\pm$ 45.2	6.7 $\pm$ 11.5	0.0 $\pm$ 0.0	0.2 $\pm$ 0.3
					0.1 $\pm$ 0.2	0.0 $\pm$ 0.1

Table 4. Model results for catch rates (log-transformed) including significance levels. Smooth terms and random terms given as estimated degrees of freedom (edfs).

Species	$\eta$	Predictors							Explained deviance	
		Categorical term estimates				Smooth term (edfs)				
		Gear (trawl)	Mesh	Season	Target	Depth	Latitude	Vessel		Trip
Cod	2.3***				Plaice (-0.5)**	2.8***	7.6***	34.2***	128.8***	72.1%
Dab	0.3*				Dab (5.3)**	2.9***	4.4***	36.1*	112.7***	88.9%
Haddock	0.6***			4 (0.5)*		3.0***		38.3**	133.2***	87.0%
Hake	-3.1***			2 (1.5)** 3 (1.9)*** 4 (1.8)***	Haddock (-0.6)** Norway lobster (1.1)***	1.0***	9.0**	58.7	128.9*	88.7%
Herring	-1.9***			3 (-1.6)*	Plaice (-2.7)***	2.4**		25.7	83.1*	91.3%
Lemon sole	0.1			2 (0.6)**	Dab (3.2)* Norway lobster (-1.4)*** Saithe (-1.3)*	2.8***	4.8**	21.9	93.5***	77.8%
Norway lobster	14.7***		-0.1***		Haddock (-1.8)** Norway lobster (2.2)*** Plaice (-3.9)***	2.5***		50.3**	85.2**	97.7%
Norway pout	-4.9***				Norway lobster (1.5)***	3.0***	7.8***	49.4	63.2	89.6%
Plaice	2.9***	-0.9***		4 (-0.6)***	Dab (3.7)*** Norway lobster (-0.7)*** Plaice (0.5)***	2.8***		34.3	127.3*	92.3%
Saithe	-5.9***	1.1**	0.0*	2 (1.5)*** 3 (1.3)*** 4 (1.3)***		2.8***	1.4*	0.0	123.5***	92.6%
Whiting	5.0**	1.2*	-0.0*	2 (-2.0)*** 3 (-1.3)*** 4 (-0.8)*	Plaice (-1.7)***	2.7***		36.6	128.0*	89.8%
Witch flounder	4.5***	-1.3***	-0.0***		Witch flounder (0.5)*	2.9***	2.1*	13.6	111.3***	85.3%

Significance levels: \*p < 0.05, \*\*p < 0.01, \*\*\*p < 0.001;  $\eta$  = intercept (gear: Danish seine, season: 1, target: cod)

Significance levels: \*p < 0.05, \*\*p < 0.01, \*\*\*p < 0.001;  $\eta$  = intercept (gear: Danish seine, season: 1, target: cod)

Mean values of the MS ratios ranged from 0% (hake: all categories except trawls 90 - 109 mm, Norway lobster: trawls  $\geq$  110 mm, saithe: all categories except for trawls  $\geq$  110 mm, witch flounder: seines 90 - 109 mm) to 50% (Norway lobster: seines 90 - 109 mm and trawls 90 - 109 mm, plaice: seines  $\geq$  110 mm, whiting: both seine categories, Table 3) and differences between the gear and mesh categories were small (Table 5). Gear was found to significantly affect the MS ratio of whiting (lower for trawls) and mesh size affected the ratios of haddock negatively. Season was significant for four species (cod, dab, plaice, whiting), whereby season four was often the decisive season (lower ratios). Target species significantly affected ratios of four species (cod, dab, haddock, Norway lobster), where Norway lobster significantly increased the ratios of cod and haddock. The smooth terms depth and latitude were significant factors for five (cod, haddock, hake, whiting, witch flounder) and one species (Norway lobster), respectively. Random effects were also found to be of high importance; only cod did not show any significant effects of those (Table 5).

Table 5. Model results for minimum size ratio (individuals below minimum landing size or minimum conservation reference size/total no. of individuals, logit-transformed) including significance levels. Smooth terms and random terms given as estimated degrees of freedom (edfs).

Species	$\eta$	Predictors								Explained deviance
		Categorical term estimates				Smooth term (edfs)				
		Gear (trawl)	Mesh	Season	Target	Depth	Latitude	Vessel	Trip	
Cod	-1.6***			4 (-1.1)***	Norway lobster (0.6)*	3.0***		80.3	117.2	72.0%
Haddock	2.1		-0.0**		Norway lobster (1.2)*** Saithe (1.4)**	2.2***		24.0***	12.3	45.8%
Hake	-5.3					2.0***		61.2	74.0*	89.9%
Norway lobster	-0.7*				Haddock (-1.3)*					
					Norway lobster (-1.2)***		1.0**	35.7***	32.6	64.7%
					Saithe (-0.9)*					
					Witch flounder (-1.8)***					
Plaice	-1.9***			4 (-1.2)**				80.6*	116.9**	78.6%
Whiting	-1.0**	-1.0*		2 (1.0)** 4 (-1.1)**		1.2***		21.9	69.4*	67.7%
Witch flounder	-3.9**					1.0**		69.1	113.1***	89.4%

Significance levels: \*p < 0.05, \*\*p < 0.01, \*\*\*p < 0.001,  $\eta$  = intercept (gear: Danish seine, season: 1, target: cod)

## Discussion

Fishing operation and catch profiles of commercial species for seiners and trawlers fishing in the Skagerrak and the northern Kattegat were compared based on 16 years of Danish observer coverage. This represents a comprehensive data source to evaluate and determine how specialized and flexible the two gears are in terms of target species and catches of fish below MS. The collected data is used to indicate how appropriate the legislative grouping of seines and trawls is and how challenged the two fisheries will be in meeting the objectives of the landing obligation.

Higher flatfish catch rates were observed for seines than for trawls despite having lower engine power with an expected lower fuel consumption and CO<sub>2</sub> emissions, as also reported by Thrane (2004). Such results demonstrate that seining is an energy efficient way of catching plaice and other flatfish species. Seiners generally fished in shallower waters than trawlers and are likely more restricted to flat and sandy areas to avoid damage to the seine ropes and lighter ground gears from stony bottoms. Contrary, trawlers use sweeps which are much shorter than seine ropes and trawls are often equipped with devices like bobbins or use rockhopper ground gear designs to protect the netting from damage by rough bottoms (He and Winger, 2010). This makes trawlers more flexible as they can operate on more diverse fishing grounds which explains the longer list of target species for trawlers than for seiners.

Very low R<sup>2</sup> values in the ANOVA approach as well as the results of the GAMM approach highlighted the importance of parameters else than gear and mesh size in determining catch rates and MS ratio. Conditional parameters such as latitude or season and random effects (vessel and/or trip) were found to have significant effects on the catches of most species. This may indicate that it is primarily not the gear or mesh size that is directly responsible for differences in MS ratios or catch rates between the two fishing methods, but more likely the specific conditions in which the gears are used. As these conditions include area and depth as factors of high importance in determining the catch rate and the proportion of fish below MLS or MCRS, differences in the catches are likely between different regions and habitat types. This suggests including area aspects to technical aspects in management plans. The unexpectedly weak effect of mesh size on catch rate and particularly MS

ratio has also been observed previously using similar observer collected data. Feekings et al. (2012) were inconclusive about the importance of mesh size on the discard rates of plaice and suggested that the heterogeneity in the sampling across mesh sizes and other factors was likely the cause of this phenomenon. The high importance of vessel and/or trip as random effects in determining catches was also found by several other studies (Tschernij and Holst, 1999; Poos and Rijnsdorp, 2007; Feekings et al., 2013). There may, however, be other influential factors that could affect catch rates or MS ratios. This could be ecological factors or other technical factors (e.g. selective devices, quota availability). Although the regulations in the study area changed several times in the study area, potential effects on catches of seines and trawls were considered to be similar because both belong to the same legislative category (Council Regulation (EC) 850/98). Nevertheless, the quality of the data collected within the observer programs could be improved by a more precise recording of additional factors like an accurate description of used selective devices. As it could also be possible that conditional factors are linked and interact, effects of gear or mesh size were maybe confounded or masked in the present study. To account for this, future studies that compare catches of seiners and trawlers should ensure that additional factors like area, depth, or season are the same for both gears.

Despite the pronounced effects of conditional parameters, significant differences were found in catch rates between seines and trawls for several species, indicating catch rates of flatfish to be generally higher for Danish seines and catch rates for roundfish species to be higher for trawlers. Significant differences in MS ratios were only found for whiting which is not directly targeted. Thus, the results of this study provide no clear findings to challenge the legislative grouping of seines and trawls into the same category. In the context of the landing obligation system, the results indicate that both fisheries will be affected as both gears caught fish below MCRS by ratios of up to 50%, e.g., for the most important target species of both gears (Norway lobster and plaice, respectively). The minor differences in MS ratios between the gears indicate that challenges like the handling and storage (Sardà et al., 2015) or the later sale of this less valuable part of the catch are probably similar for both gears. To account for the mismatch in the size of caught Norway lobster and MLS (carapace length: 40 mm), the MCRS is reduced to 32 mm carapace length. However, the approach of excluding

mesh sizes below 90 mm in the present study in order to compare only similar mesh sizes likely ignored considerable amounts of Norway lobster and fish below MS in trawl catches. The majority of the trawl fleet in the Skagerrak/Kattegat area used mesh sizes below 90 mm until 2005 to fish for their main target Norway lobster, which requires the use of small mesh sizes (Krag et al., 2008). Today they use a mesh size of 90 mm. The smaller fleet of seiners usually uses larger mesh sizes as they do not target Norway lobster. Mesh sizes of 120 mm are normally used to avoid catches of smaller fish. For fish-targeting fisheries, an obvious way to reduce the amount of small individuals could be an increase in the codend mesh size (Glass, 2000; Krag et al., 2008). In crustacean targeting fisheries, selective devices (e.g., escape panels or grids) are an option to exclude unwanted fish (e.g., Valentinsson and Ulmestrand, 2008; Frandsen et al., 2009), but research is still needed to improve their selectivity properties. This study showed that trawling is an opportunistic and more flexible fishing method which can target several different species on a variety of different substrates, whereas seining is specialized on catching primarily flatfish efficiently. Highly specialized fishing gear can be challenged in fast changing biological and management systems. Contrary to trawlers, seiners will not have the opportunity to switch to other fisheries in the case of low market prices or low quotas. Therefore, combining the advantages of trawlers and seiners could be a conceivable approach which is already recognized by the industry as several of the new fishing vessels coming into the fleet are combination vessels capable of both trawling and demersal seining (Scottish seining or fly-shooting). Such combination vessels give the fishermen high efficiency in the available fisheries and a high flexibility to continuously optimize the catch composition as needed under the new landing obligation to optimize the vessel's quota capitalization.

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## Supplementary material

Table S1. Catch rate (individuals/h) as mean value  $\pm$  standard deviation including dfs (degrees of freedom) and adjusted  $R^2$  as measure of explained deviance. Mean values that are not sharing a letter (a, b, c) are significantly different (two-way ANOVA and post-hoc Tukey-HSD test;  $\alpha \leq 0.05$ ).

Species	Catch rate				dfs	adj. R <sup>2</sup>
	90 - 109 mm		≥ 110 mm			
	Seine	Trawl	Seine	Trawl		
Cod	47.7 ± 48.3 a	38.3 ± 51.9 a	54.2 ± 109.2 a	47.2 ± 64.4 a	741	0.00
Dab	38.3 ± 75.8 a	51.8 ± 127.2 a	74.6 ± 178.2 a	40.9 ± 142.1 a	741	0.00
Haddock	38.3 ± 47.5 ab	40.9 ± 82.8 ab	33.1 ± 76.8 a	62.2 ± 115.2 b	741	0.01
Hake	2.6 ± 5.6 ab	5.0 ± 10.2 b	1.9 ± 8.0 a	1.1 ± 2.2 a	741	0.03
Herring	0.2 ± 0.7 a	2.5 ± 8.0 b	0.3 ± 2.1 a	1.0 ± 4.1 ab	741	0.03
Lemon sole	14.6 ± 14.5 b	6.4 ± 21.1 a	5.1 ± 12.3 a	8.2 ± 14.6 ab	741	0.02
Norway lobster	0.0 ± 0.2 a	971.2 ± 1952.0 b	0.0 ± 0.0 a	30.2 ± 153.5 a	741	0.10
Norway pout	0.1 ± 0.8 ab	5.3 ± 27.1 a	0.1 ± 0.8 b	0.5 ± 2.7 ab	741	0.01
Plaice	280.1 ± 689.7 b	60.3 ± 148.4 a	481.1 ± 849.7 c	146.1 ± 194.1 ab	741	0.11
Saithe	2.7 ± 14.0 ab	15.3 ± 49.1 b	3.9 ± 44.6 a	22.5 ± 82.8 b	741	0.01
Whiting	0.9 ± 2.2 a	20.8 ± 37.1 b	1.1 ± 4.3 a	4.1 ± 9.1 a	741	0.11
Witch flounder	33.2 ± 63.1 b	17.1 ± 30.7 a	17.4 ± 45.2 a	6.7 ± 11.5 a	741	0.02

Table S2. Minimum size (MS) ratio (individuals below minimum landing size (MLS) or minimum conservation reference size (MCRS)/total no. of individuals)  $\pm$  standard deviation including dfs (degrees of freedom) and adjusted  $R^2$  as measure of explained deviance. Mean values that are not sharing a letter (a, b, c) are significantly different (two-way ANOVA and post-hoc Tukey-HSD test;  $\alpha \leq 0.05$ ).

Species	MS ratio				dfs	adj. R <sup>2</sup>
	90 - 109 mm		≥ 110 m			
	Seine	Trawl	Seine	Trawl		
Cod	0.2 ± 0.2 ab	0.4 ± 0.3 c	0.3 ± 0.3 b	0.1 ± 0.2 a	693	0.08
Haddock	0.1 ± 0.2 a	0.4 ± 0.4 b	0.2 ± 0.3 a	0.1 ± 0.2 a	543	0.17
Hake	0.0 ± 0.0 a	0.2 ± 0.3 b	0.0 ± 0.0 a	0.0 ± 0.1 a	388	0.11
Herring	0.2 ± 0.4 a	0.1 ± 0.3 a	0.4 ± 0.4 a	0.2 ± 0.3 a	173	0.02
Norway lobster	0.5 ± 0.0 ab	0.5 ± 0.3 b	0.0 ± 0.0 a	0.3 ± 0.3 a	284	0.04
Plaice	0.2 ± 0.2 a	0.4 ± 0.4 bc	0.5 ± 0.4 c	0.3 ± 0.4 ab	664	0.05
Saithe	0.0 ± 0.1 a	0.0 ± 0.1 a	0.0 ± 0.2 a	0.1 ± 0.2 a	345	0.00
Whiting	0.5 ± 0.4 b	0.4 ± 0.3 b	0.5 ± 0.4 b	0.1 ± 0.2 a	372	0.06
Witch flounder	0.0 ± 0.0 a	0.2 ± 0.3 b	0.1 ± 0.2 a	0.0 ± 0.1 a	501	0.14

DTU Aqua – National Institute of Aquatic Resources – is an institute at the Technical University of Denmark. DTU Aqua's mission is to conduct research, provide advice, educate at university level and contribute to innovation in sustainable exploitation and management of aquatic resources. We investigate the biology and population ecology of aquatic organism, aquatic physics and chemical processes, ecosystem structure and dynamics, taking account of all relevant natural and anthropogenic drivers.

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